Volume 27 DECEMBER, 1957 Number 4

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

DEC 24 1957

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The *Journal of Sedimentary Petrology* is published by the Society of Economic Paleontologists and Mineralogists, a division of The American Association of Petroleum Geologists. Numbers are issued in March, June, September and December.

The subscription price of the *Journal of Sedimentary Petrology* is $6.00 per year prepaid to addresses in the United States.

Single numbers, $2.00 each ($1.50 to members).

Postage is charged extra for all other countries: 40 cents on annual subscriptions (total $6.40).

The *Journal* will furnish reprints at cost. Orders should accompany corrected galley proof.

Communications about *Journal* subscriptions, rates, memberships, change of address, and non-receipt of preceding number should be addressed to Society of Economic Paleontologists and Mineralogists, P.O. Box 979, Tulsa, Oklahoma. Claims for non-receipt of preceding numbers must be sent in within three months of the date of publication in order to be filled gratis.

Communications in regard to manuscripts and purely editorial matters should be addressed to The Editor, *Journal of Sedimentary Petrology*, University of Illinois, Urbana, Illinois.

Annual Membership dues, including the Journal of Paleontology .....$ 8.00
Annual Membership dues, including the Journal of Sedimentary Petrology .. 5.00
Annual Membership dues, including both Journals 13.00

Non-Member Subscriptions to Journal of Paleontology $15.00; Outside U.S. $15.40
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$6.00; Outside U.S. $6.40

GEORGE BANTA COMPANY, INC., MENASHA, WISCONSIN
PRINTED IN THE U.S.A.

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NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

Second-class mail privileges authorized at Menasha, Wisconsin.

Among papers to appear in forthcoming issues of the *Journal* are the following:

Cyclic patterns in mechanically deposited Pennsylvanian limestones of northeastern Nevada. By R. H. Dott, Jr.

A new technique for measuring roundness of sand grains. By D. A. Robson.

Evaporite facies. By L. I. Briggs.

The petrology of the Whita Sandstone, southern Scotland. By A. E. M. Nairn

Size distribution of zircon grains in some samples of the lower Beaumont Clay. By J. J. W. Rogers and W. F. Powell.

A proposed classification and terminology of rocks in the series bauxite-clay-iron oxide ore. By Jiří Konta.

An occurrence of flat-topped ripple marks. By W. F. Tanner.

Heavy mineral variation in San Antonio and Mesquite Bays of the Central Texas Coast. By D. M. Poole.

Sedimentary analysis of terrace deposits in panhandle Florida. By W. J. Lapinsky, S. R. Revell, and S. S. Winters.

Petrography and porosity of the Cow Run Sand, St. Marys, West Virginia. By J. C. Griffiths.

Alteration of volcanic ash near Denver, Colorado. By J. Schlocker and R. Van Horn.

Size distribution of rock types in steam gravel and glacial till. By S. N. Davis.

Two undescribed structures in a greywacke series. By A. Wood and A. J. Smith.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 4, PP. 355–372
FIGS. 1–7, DECEMBER, 1957

ADJUSTMENT OF LAND DERIVED CLAYS TO THE MARINE ENVIRONMENT[1]

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ABSTRACT

The predominant clay minerals found in the waters of rivers in the area of Chesapeake Bay consist of a well-formed to weathered illite with minor amounts of kaolin and a trace of weathered chlorite. Mixed-layer clays were observed in the estuaries and are related to and difficult to distinguish from differentially hydrated monomineralic clays when these clays are in a weathered condition. A regularly stacked mixed-layer illite-chlorite was observed at one locality in the James Estuary.

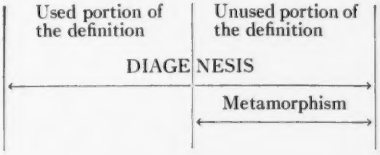
A chlorite-like and vermiculite clay are forming in estuaries along the Atlantic Coast. Thermal stability of the diagenic chlorite increases with increasing salinity of the environment and to less extent with depth in the sediment. The chloritic material arises principally from the diagenesis of weathered illite in the Atlantic Coastal environment and probably passes through a vermiculite stage. Montmorillonoid, and to less extent illite, are altered to a chloritic material in the Gulf of Mexico and along the Pacific Coast.

The first phase planned for the study of the geochemical relation of chloride, sodium, calcium, potassium, and magnesium in the clays of an estuary has been completed. The chemical data lend support to the hypothesis that a chloritic-vermiculitic clay mineral is being constructed by the alteration of weathered illite and montmorillonoid, and the reconstitution of a trace amount of chlorite.

INTRODUCTION

New data from the author's laboratory and the literature have come to light on the subject of the alteration or diagenesis of clay minerals since the writing of an earlier paper (Powers, 1953). Reference is made in this paper specifically to alterations in clays that have shifted or were in the process of shifting from the fresh to the salt water environment of the oceans at the time of sampling. Several hundred samples have been investigated by one or more of the following techniques, including X-ray, D.T.A., electron microscopy, and chemical analysis. Interest is centered on the chemical rather than the physical change of the environments because the latter has but little bearing on the subject.

Definitions.—Alteration refers to a change, modification, or transformation. Diagenesis is defined by Rice (1948) as a "recombination or rearrangement resulting in a new product, as in the formation of larger crystalline grains from smaller ones." In turn, the word "product" may be defined as "the result of chemical change" (Funk and Wagnalls, 1943). It would seem from these definitions that diagenesis refers simply to the chemical or physical alteration of a material and is not limited to maximum or minimum pressure-temperature conditions. The fact that this definition overlaps and in fact includes the definition of metamorphism does not hinder its use; for the definition of metamorphism (see Tyrrell, 1929) limits the "usable" part of the definition of diagenesis. In this way diagenesis does *not* refer to "pronounced changes of temperature, pressure, and chemical environment which takes place, in general, below the shells of weathering and cementation" (Tyrrell, 1929). If such changes do come about, the term metamorphism should be used in place of diagenesis. On the other hand, diagenesis is not limited to standard temperature-pressure conditions and therefore may take place at considerable depth below the *surface* of the earth. The relation of the two terms to each other may be illustrated graphically in terms of their definitions as shown below.



There is no attempt to correctly portion the lengths of the bar to the terms.

It may be concluded that the term dia-

[1] This work was done from 1952–1954 at the Chesapeake Bay Institute of the Johns Hopkins University and the University of North Carolina. Manuscript received December 28, 1956.

genesis is practically synonymous with alteration and, as such, has an important usage in geological terminology. The term "diagenic chlorite" is used in this paper as before (Powers, 1953) to refer to a chlorite-like clay mineral formed through diagenesis. The "diagenic chlorite" actually consists of a chlorite and vermiculite clay. The two clays are quite similar chemically and difficult to define, except by special heat treatments followed by X-ray diffraction. The oscillating-heating X-ray diffractometer is ideal for studying complex mixtures of clays of the type investigated (Weiss and Rowland, 1956).

LITERATURE REVIEW

Data on the diagenesis of clays in Recent marine sediments and the presence of chlorite in marine shales are notably lacking. Grim pointed out that chloritic mica and illite almost certainly form during marine diagenesis (Grim, 1953, p. 352). He says that chlorite may form from kaolinite and that illite forms from montmorillonite, although these alterations take place slowly. Grim states that degraded illite and chlorite from rivers would be quickly reconstituted to more perfect structures. Grim and Johns (1953a) have studied clays along portions of the Gulf of Mexico. They report that the bulk of the argillaceous fraction is composed of illite, montmorillonite, and chlorite. In another paper these authors suggest the formation of a poorly crystalline illitic and chloritic phase in the Gulf sediments (Grim and Johns, 1953b). The present author independently arrived at somewhat similar conclusions based on studies in the Gulf of Mexico and in the Chesapeake Bay area (Powers, 1953).

In 1953 Haydn H. Murray reported the clays in the sediments from Norfolk, Virginia, to Bermuda to consist predominantly of illite, chlorite, and kaolinite (personal communication, 1953). Murray also reported chlorite, illite, and kaolinite present in Pennsylvanian shales of Indiana and Illinois (Murray, 1953b). Murray and Sayyab (1955) state that . . . "studies of the clay minerals (off the coast of North Carolina) reveal that a slight diagenetic change takes place as indicated by increasing crystallinity of chlorite and illite with increasing water depth."

Millot studied marine sediments, mainly Triassic and Jurassic age, from the Paris Basin in France and found illite to be the dominant clay mineral in most samples studied. Chloritic mica and vermiculite were frequently present as minor constituents (Millot, 1949).

Siever found illite, chlorite, and kaolinite in samples from upper Chester sandstones (Siever, 1953). He interprets the presence of chlorite as suggesting deposition in brackish or marine waters.

Griffin has reported chlorite, illite, and kaolinite in samples from the Neuse River Estuary (Griffin and Ingram, 1955). Griffin reported an increase in "chlorite" and illite in a down-estuary direction. He pointed out that the "chlorite" was thermally unstable when heated to 400° C for one hour.

Caillère and Hénin (1949) reportedly formed chlorite from montmorillonite in the laboratory under standard temperature-pressure conditions.

Whitehouse (1956) exposed kaolinite, montmorillonite, and illite to artificial sea water for periods of six months to four years. He reports the formation of chloritic and illitic clay types from montmorillonite.

Caillére, Oberlin, and Hénin (1954) found the pH and temperature important factors in the synthesis of clay minerals in the laboratory.

Weaver (1953b) suggested that some of the volcanic ash deposited in the Ordovician carbonate rocks had altered to chlorite, and in 1956 reported the presence of chlorite in sediments of continental, transitional, and marine environments.

SEDIMENTATION IN THE CHESAPEAKE BAY AREA

A composite of several thousand core, scoopfish, and grab samples have been taken in the Chesapeake Bay, some of its estuaries, and in the adjacent continental shelf. A large amount of data have been accumulated from field and laboratory investigation of the samples in connection with an investigation for the Office of Naval Research and the United States Hydrographic Office.

Analysis of the accumulated data has revealed a regular pattern of sedimentation in the estuarine and nearshore areas in the vicinity of Chesapeake Bay. In the fresh

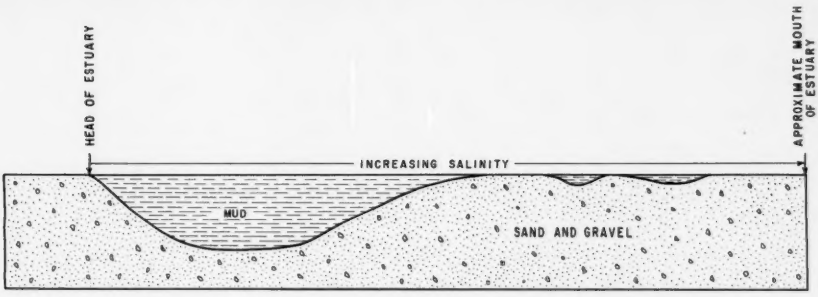


FIG. 1.—Schematized cross section along the channel of an estuary assuming a still-stand in sea level.

water environment of the rivers, mud invariably occurs in the shoal areas and sand to cobble-size particles occur in the channels. In the estuary the picture is reversed, so that mud, when present, occurs in the channels and sand occurs in the shoal areas. The explanation of this reversal of position of the mud and sand is not definitely understood, but it is dependent in part on eddy movement. The eddy system caused by differential current velocity and direction is one in which the eddies spiral inward and downward toward the deep channels. For this reason there is a constant potential for the movement of suspended clay particles toward the channels. Immediately next to the bottom along a sloping surface eddy movement is toward the shoal areas. This tends to move the deposited sediment away from the channel. Once deposited, the mud is difficult to erode, whereas the sand, which is eroded only by saltation and mass movement along the bottom, is relatively easier to erode by low current velocities.

Even if the bottom eddy velocities are not great enough to prevent the sand from reaching the channel, another factor preserves the pattern of muddy channels and sandy shoal areas in the estuary. As sand is moved toward the muddy channels, it infringes on the mud-sand boundary. The sand sticks in the plastic mud and further erosion toward the channel is prevented. The only sand that reaches the channel has to do so in suspension and thus rides over the plastic mud. Water sampling in Chesapeake Bay and the James Estuary indicates that there is no sand carried in suspension. The sand might also reach the channel if, by virtue of its relatively greater quantity, it could smother and override the mud. In this case sand would be found in the channel and shoal areas. The occurrence of mud in the channels and sand in the shoal areas is very likely a general condition that would probably apply to most types of estuaries.

Along the flow direction of the estuary there is also a regular pattern of sedimentation. The shoal areas consist of sand along the entire length of the estuary. Cross sections along the channels of the Patuxent and James Estuaries, as well as the Chesapeake Bay, show an elongated lens of mud which begins near the fresh water boundary and extends downstream for many miles. The lens pinches out both in an upstream and a downstream direction, having its maximum thickness between these extremes but nearer the upstream boundary (fig. 1). The figure does not attempt to show the effect of transgressions or regressions on the mud lens. This distribution of mud along the length of the estuary is caused by the flocculent effect of the brackish water on the clays.

As flocculation proceeds, the downstream water is depleted of its suspended load. Flocculation is therefore less likely because of fewer available particles. The flocculation hypothesis can thus explain why only a very small fraction of the river suspension load finds its way beyond the estuarine trap and accounts for the elongated lens of mud in the estuaries.

Most of the evidence is against any scouring action in the estuarine channels. A comparison of old and recent navigation charts shows that water depths have become shallower and suggests that the muds are not

TABLE 1.—*Age of sediments in the James Estuary*

Depth below surface (feet)	Age in years
0	0
0.5	1–10
5	75–125
10	400–600
15	900–1000
20	1500–1700
30	3000–3200
35	3900–4100

eroded. Based on a comparison of water depth in undredged channels from recent and 100-year old navigation charts, and taking into consideration the vertical differential compaction of muds (Emery and Rittenberg, 1952), the James Estuary sediments have roughly the ages as shown in table 1.

Ryan (1953) reports the presence of detrital coal in sediments of the upper reaches of Chesapeake Bay. The coal occurs in relatively smaller amounts below about five feet in his cores than above five feet, and no coal has been found below the mouth of the Patapsco River. Presumably this coal was carried down to Chesapeake Bay by the Susquehanna River and has been deposited in large volumes since the early days of coal mining along the Susquehanna River. It is difficult to tell just when coal was first dumped into the river, but the rate of deposition based on such a method of comparison would be of the same order of magnitude as determined for the James Estuary by using old and recent navigation charts.

Evidence that the source of most of the clays is from the river rather than from the shoreline of the estuary lies in the close relation between the occurrence of muds in the estuaries and salinity, and the absence of any association of channel muds and clay-bearing formations that crop out along the estuaries.

INVESTIGATION BY X-RAY POWDER DIFFRACTION IN THE CHESAPEAKE BAY AREA

Figure 2 shows the location of a selected number of inshore cores, grab samples, and suspended sediment samples used to illustrate the various processes discussed in this paper. Location of offshore cores, as well as field data for the discussed samples, are given under the discussion of individual samples. A map showing the location of all samples studied is not available because of military restrictions.

Sample Preparation

The clay samples were X-rayed after one of more of the following preparations:

1.—Clay particles were separated from bulk sample by sedimentation in water and X-rayed as an oriented aggregate and capillary-tube mount.

2.—Oriented aggregates were X-rayed after saturation with glycerine.

FIG. 2.—Map showing selected group of cores, grab samples, and suspend sediment samples.

3.—Untreated oriented aggregates were X-rayed individually after or during heat treatments ranging from 50 to 700° C.

4.—Samples were X-rayed as oriented aggregates after first boiling in ammonium chloride, then after boiling in magnesium acetate, and again after boiling in potassium acetate.

5.—Samples were X-rayed after leaching with dilute HCl.

This combination of preparations enables the observer to differentiate between vermiculite (Walker, 1951), chlorite, and hydrous mica (Rolfe and Jeffries, 1952). The temperature treatments allow a rough determination of the thermal stability of the minerals as well as differentiating between montmorillonite, chlorite, and vermiculite. The identification of mixed-layer clays by X-ray powder diffraction and their occurrence in sediments has been reported by several authors, including Brown and MacEwan (1951), Bradley (1953), Brindley and Gillery (1953), Grim (1953), Hendricks and Teller (1942), and Weaver (1956a). Weaver's paper includes a rather full account of identification techniques for commonly occurring mixed-layer clays. Randomly interstratified mixed-layer clays described by the above-mentioned authors are rarely seen in the Recent marine sediments investigated by the author. A random mixed-layer stacking arrangement does appear to result from ion exchange and differential hydration of weathered clays coupled with a regeneration of some of the weathered or degraded clays. The mixed-layer phase that occurs is apparently somewhat limited to a narrow transition range within the estuary, and the quantity is probably statistically related to exchange reactions occurring in the estuary.

Results from X-ray

Bottom water or bottom water layer, as used in this paper, refers to the first few feet of water overlying the sediments. Salinity values of bottom water given in this paper are only approximations to average values, since salinity may vary widely because of tidal, seasonal, and other influences.

Table 2 summarizes X-ray results on samples reported in an earlier paper (Powers, 1953). This paper states the techniques employed in X-ray diffraction and the quanti-

TABLE 2.—*Summarizing X-ray results on samples reported in earlier paper**

Sample No.	1	2	3	4	5	7 and 8
Sample Location	Bottom Surf. Patuxent River	Bottom surf. Patuxent Est.	Top 6″ of core—Patuxent Est.	Top 6″ of core—Patuxent Est.	Top 6″ of core—York Estuary	Top 6″ of core. 80 and 400 miles east of Roanoke Island
Clay minerals present and approx. percentage of clay fraction	Illite—50% W.† illite—35% Kaolinite—15% W. chlorite-Trace	Very little change from Sample 1. Perhaps 10% M.L. illite-chlorite and 25% W. illite	Illite—50% M.L.‡ illite-chlorite—15% Kaolinite—15% Chlorite—20% W. illite-Trace	Illite—40–45% M.L. illite-chlorite—15% Kaolinite—15% Chlorite—30%	Illite—40% M.L. illite-chlorite—15% Kaolinite—15% Chlorite—30–35%	Illite—40% Chlorite—45% Kaolinite—15% W. illite-Trace (?)
Salinity of water (parts per thousand)	Fresh	1–3	5–7	17	23–25	35–36
Approx. thermal stability of diagenic chlorite	200° C	About 300° C	About 350° C	350° C 500° C	About same as Sample 4	500° C 14 Å line intensified by heating to 500° C

* Tables and graphs cannot adequately illustrate complex multicomponent and mixed-layer clays. The paper must be consulted in order to appreciate the composition more fully.

† W.—Weathered clay differentially hydrated producing a band.

‡ M.L.—Mixed-layer clay plus differentially hydrated clay.

tative estimation of the clays from diffraction data.

Samples from the James Estuary.—Samples 11 through 16 were taken in the James Estuary (fig. 2), and showed about the same diagenetic trend as outlined for samples 1 through 4 in table 2. Suspended sediment samples from the James Estuary (fig. 2) show no significant difference from the deposited material for a given position in the estuary.

Sample 11.—This sample was taken from the top of a core in the James Estuary near Jamestown Island. The bottom water here has a salinity of about one part per thousand. The photograph of a sample that was dried for several hours at 50° C showed diffraction maxima at 17.1, 13.9, 9.9, 8.4, 7.1, and a weak maximum at 4.8 Å (table 3). The 17.1, 8.4, and 4.8 Å lines contribute to a rational sequence of numbers related to a 34 Å basal spacing, and suggest a regular interstratification of two parts illite to one part chlorite (Brown and MacEwan, 1951, p. 266–267). The drying procedure would have caused the 17 Å maximum to shift to a smaller spacing had it been caused by a montmorillonoid. After treatment with glycerine, the 14 Å line did not shift, suggesting the presence of a chlorite or weathered illite. Saturation of the sample with potassium caused a weakening in the intensity of the 14 Å line, which could be intensified again by subsequent saturation with magnesium. The weakening of the 14 and 10 Å lines, respectively, by saturation first with potassium

TABLE 3.—*X-ray diagrams of estuarine clays**

Sample 11		Sample 11a		Sample 16	
d (Å)	I	d (Å)	I	d (Å)	I
14.5		17.1	4	14.0	
14.1	3	14.5		13.9	4
9.8	6	13.9	4	9.9	7
9.5		9.9	6	9.8	
7.1	6	9.3		7.1	6
4.85	1B	8.4	3	4.98	1B
Q 4.21	3	7.1	6	4.46	3
3.57	6	5.64	1B	Q 4.21	3
Q 3.35	10	4.80	2	3.54	3
2.54	1	4.46	1	Q 3.35	10
Q 2.45	1	Q 4.21	6	3.19	3
Q 2.29	1	3.56	3B	2.97	2
Q 2.13	3	Q 3.35	10	2.85	2B
Q 1.997	2B	3.22	2B	2.56	3B
Q 1.814	4	2.97	1B	Q 2.45	1
Q 1.667	3	2.83	3B	2.39	1B
Q 1.539	3	2.57	2	Q 2.28	1
1.499	1B	2.53	1B	2.21	1B
1.463	1B	Q 2.46	1	Q 2.12	2
		2.37	1B	Q 1.998	5B
Q 1.376	2	Q 2.12	2	Q 1.814	4
		Q 2.00	4B	Q 1.667	2
		Q 1.814	6	Q 1.539	3
		1.743	3B	1.497	1
		Q 1.539	4	1.463	1
		1.499	1B	1.430	1
		Q 1.376	5	Q 1.376	4
		1.293	1B	1.297	2B
		1.260	1B	1.258	2
		1.205	1	1.202	3
		1.187	1	1.195	3
				1.099	1

* B = broad or diffuse. Q = quartz.
Sample 11 = suspended sediment from top water layer at position of core 11 (fig. 1), dried at 50° C, glycerine saturated, oriented aggregate.
Sample 11a = top six inches of core 11 (fig. 1), dried at 50° C, untreated, oriented aggregate.
Sample 16 = grab sample at position of core 16 (fig. 1), heated at 350° C, oriented aggregate.

and then with magnesium suggests the presence of chlorite, illite, and weathered illite.

A prominent 7 Å line persisted through all of the above-mentioned treatments and is caused by the presence of kaolinite. After heating the sample to 200° C, strong 7 and 10 Å maxima persisted, as well as a band from 10 to 14 Å, with a very slight peak in the 14 Å region. The 10 and 14 Å band suggests different states of hydration in the chlorite-like material, perhaps caused by complete to partial collapse of the diagenic structure at this temperature. The slight peak at 14 Å may be related to a detrital weathered chlorite of metamorphic origin. The 14 Å line did not entirely shift after treatment with potassium, and it did not fully rehydrate after heating to 200° C, suggesting the presence of both vermiculite and chlorite in the sample.

When the sample was heated to 300° C and X-rayed, the films showed only sharp lines at 10 and 7 Å. The presence of kaolinite is therefore verified. The sample was subsequently heated to 500° C, at which temperature the 7 Å kaolinite diffraction maximum disappeared.

Leaching the original sample for one-half hour in 1.0N hydrochloric acid caused a dark band to appear in the X-ray photograph, reaching from 10 to 14 Å. This band is probably caused by partial to complete hydrogen ion replacement along the (00*l*) surfaces of degraded illite and chlorite with accompanying various degrees of hydration.

In summary, the bottom sediments near the head of the James Estuary contain kaolinite, illite, westhered illite, a small amount of diagenic chlorite, and some mixed-layer chlorite-vermiculite. The diagenic chlorite is subject to weak thermal and chemical decomposition, converting to a hydrous mica-like material. At least some of the diagenic chlorite seems to occur regularly interstratified with illite. There is also random stacking in the clays, producing a mixed-layer illite-chlorite and chlorite-vermiculite. The manner of stacking in complex clays of this type is difficult to determine, for not only are bands and broad maxima formed by certain types of stacking, but also by the differential hydration of the clay constituents, depending on the exchange cations. One might even refer to mixed hydration as a common property of these clays and the term mixed-layer may be applied to this material.

Sample 12.—This sample was taken from a James Estuary core where salinity of the overlying bottom water is about 4.1 parts per thousand (fig. 2).

There was much less decomposition of the chlorite and illite when the sample was leached for one-half hour in 1.0N hydrochloric acid, thus demonstrating the relatively greater chemical stability of this clay over that of sample 11. The increase in salinity of only 3.1 parts per thousand between these two samples, and the fact that they are only ten miles apart (fig. 2) suggests the rapid rate at which the clays are constructed to a more stable type.

Sample 16.—This sample was taken from the top of a core just outside the mouth of the James Estuary (fig. 2), where the bottom water has a salinity of about 22.0 to 25.0 parts per thousand. The rational sequence related to a 34 Å basal spacing does not occur in this sample. Thermal stability of the diagenic chlorite at this location is between 350 and 400° C (table 3). The high-temperature oscillating-heating camera demonstrated the presence of vermiculite and chlorite in the sample.

No noticeable difference could be found between fine clay (less than 1.0 micron) and the coarse clay in this sample.

Summary of X-ray Observations

The same general conclusions may be stated for the James Estuary samples as for the Patuxent and Chesapeake Bay samples (Powers, 1953). Namely, a chlorite-like clay is forming from weathered illite through a mixed-layer illite-vermiculite-chlorite stage, and some illite is apparently regenerated to a better illite by K^+ fixation as shown by a sharpening of the 10 Å maximum. The important point, as will be shown later, is that Mg^{2+} is apparently adsorbed by the clays in preference to K^+, but not to the complete exclusion of K^+. The result is the increased occurrence of a chlorite-like and vermiculitic clay and to less extent illite in a down-estuary direction.

INVESTIGATION BY X-RAY IN THE ATCHAFALAYA AREA

General

Six samples from the Atchafalaya region just west of the Mississippi River delta have

been examined for their clay mineral composition. The samples were taken through the salinity profile over a distance of about 20 miles.

All of the samples are composed primarily of montmorillonoid. Kaolinite and illite are present in approximately equal amounts. The samples taken farthest offshore contain mixed-layer aggregates of illite and montmorillonoid and a chloritic material. The diagenetic sequence appears very similar to that in the Chesapeake Bay area, except that here a montmorillonoid as well as weathered illite contribute to the formation of diagenic chlorite.

Summary

Three environments may be defined by the clay mineral composition of the samples studied. The depositional environments may be designated as A, B, and C, respectively, in order of distance from shore and increasing salinity.

Environment A is defined by fresh water, and fairly rapid deposition of sediments because of loss of velocity of the river water upon entering Atchafalaya Bay. The clays present are predominantly a montmorillonoid with smaller amounts of well-formed and degraded illite and a kaolin.

Environment B is defined by salinity of about 1.0 to 10.0 parts per thousand, and rapid deposition of mud owing to the flocculent action of the salt water. Mixed-layer aggregates containing diagenic chlorite reflect the influence of the salt water. Thermal stability of the diagenic chlorite here does not exceed 200° C. The X-ray photographs suggest that the diagenic chlorite is forming from degraded illite and a montmorillonoid. The diagenic chlorite described in this environment is principally a vermiculite.

Environment C is defined by salinity of about 10.0 to 30.0 parts per thousand and less rapid deposition than in environments A or B. The maximum thermal stability of the diagenic chlorite here is 450 to 500° C.

In view of the observations outlined above, it appears that not only did a chlorite form but its thermal stability increased to more than 400° C over a total distance of only 20 miles. This is thought to be important evidence for rapid diagenesis.

INVESTIGATION BY X-RAY POWDER DIFFRACTION OF A PACIFIC CORE

General

A core taken from 12,480 feet of water in the Pacific Ocean at 30° 10′ 00″ north latitude and 120° 43′ 30″ west longitude, about 250 miles southwest of San Diego, has been investigated. The core is red brown in color and composed primarily of clay-size particles. This sediment would fall into the hemipelagic-abyssal environment of Kuenen (1950, p. 316).

The core is 60.5 inches long. At a rate of deposition of 0.5 cm per 1000 years (Kuenen, 1950) the bottom of the core would have been deposited about 290,000 years ago. The true age is probably much less than this figure.

The clay minerals in this core differ from those investigated in the Chesapeake Bay area by containing a prominent amount of montmorillonoid, and in this respect, resemble the samples studied from the Atchafalaya region.

Summary

Essentially no difference could be detected in the clay minerals in the top and bottom of the core. When dried at 50° C for several hours and X-rayed, the photograph showed 7, 10, and 14 Å lines. When saturated with glycerine, part of the 14 Å maximum shifted to 17.5 Å, and a band resulted from 14 to 17.5 Å. After heating the sample to 550° C, the 7 Å line disappeared and only a very faint line remained at 14 Å, together with a strong maximum at 10 Å.

The sample contains mostly a well-formed illite, montmorillonoid, montmorillonite-chlorite mixed-layer clay, diagenic chlorite, and about 10 percent kaolinite. The high thermal stability of the chlorite is supporting evidence of the advanced stage of diagenesis reached in this sediment.

All of the estuarine and marine samples studied so far contain a chloritic clay that is forming from degraded illite and/or montmorillonoid apparently through a mixed-layer vermiculitic stage.

FORMATION OF DIAGENIC CHLORITE IN THE LABORATORY

The clay fractions, less than 3.9 microns, were separated from a sample of weathered

Athens Shale of Ordovician age and a weathered Triassic diabase dike. The Athens clay consists almost entirely of illite with perhaps a very minor amount of a montmorillonoid. The clay fraction of the weathered diabase consists predominantly of a montmorillonoid with very minor amounts of a kaolin.

After the clays were shaken independently for 22 hours in sea water, they were washed with water and dried in a vacuum desiccator. X-ray photographs of both samples revealed the formation of a small amount of diagenic chlorite by the appearance of a 14 Å line that did not shift upon saturation with glycerine or digestion in ammonium chloride solution. Promising information could probably be gained by thus treating samples in saline water under varying salinity conditions and shaking time.

The thermal stability of an estuarine diagenic chlorite was increased from 300 to 350° C by soaking the sample in sea water for about six weeks without stirring or shaking. The increase of 50° C may have occurred very soon after soaking began. Unfortunately, this possibility was not checked.

At least these laboratory experiments offer strong evidence for two important points: chlorite can be formed from a montmorillonoid and illite by the effect of sea water, and the thermal stability of a diagenic chlorite may be increased by the effect of sea water.

INVESTIGATION BY ELECTRON MICROSCOPY

The freeze-dry technique used in sampling the suspended sediment fraction of the estuaries probably represents the first successful attempt to examine clays without materially disturbing their field condition (Powers, 1953). Other attempts result in either overly dispersing or flocculating the suspended sediment, and conclusions regarding the size and sorting characteristics of the crystals and floccules with respect to salinity, current velocity, and position in the estuary could only be highly speculative.

Suspended sediment samples showed a decrease in floccular size and a slight increase in crystal size in a down-estuary direction. X-ray and electron microscope observations on suspended sediment samples indicate without much doubt that there is no size sorting or mineralogical sorting of clay minerals in the Chesapeake Bay area.

INVESTIGATION BY CHEMICAL ANALYSES

Treatment of Samples

The James Estuary was used as a model for studying the chemistry of estuarine clays. The sediment sampling program is shown in figure 1. Samples were treated with chloroform and stored in glass jars. The pH of the cores ranged from 7.3 to 7.5.

A Buchner funnel attachment on an International size 1 centrifuge was used to extract interstitial water from the samples. This water was stored in wax-lined bottles until analyses could be performed.

The mud was then washed and dispersed in distilled water and the less-than-2.0 micron size collected. This clay was washed with water until free of the chloride ion and then one-half gram was leached for one hour with 25 cc of 1.0N HCl. These samples will be referred to as the HCl-leachate.

Total magnesium and potassium was determined for several samples of the washed HCl-leached clay. The calcium determination was a four to five percent analysis; all other elements reported were determined to one percent.

Interstitial Water

Water is squeezed out of sediments owing to compaction by overburden, and the direction of movement is in the direction of least resistance to flow. Resistance to flow will depend primarily on pressure gradients and permeability. In the upper few inches of a mud overlain by water, permeability is considerable in all directions, because the floccules are literally floated apart by the large amount of water contained in the mud. The direction of least pressure is upward during this stage of compaction and the water would probably take this path. Deeper in the mud, compression by overburden has a tendency to align the clay flakes so that their basal surfaces lie horizontally. Permeability would then probably become considerably greater in a horizontal than in a vertical direction, and the interstitial water would very likely be squeezed out laterally. Thus, with increasing depth, directional pressure becomes less important in determining the direction that the water will fol-

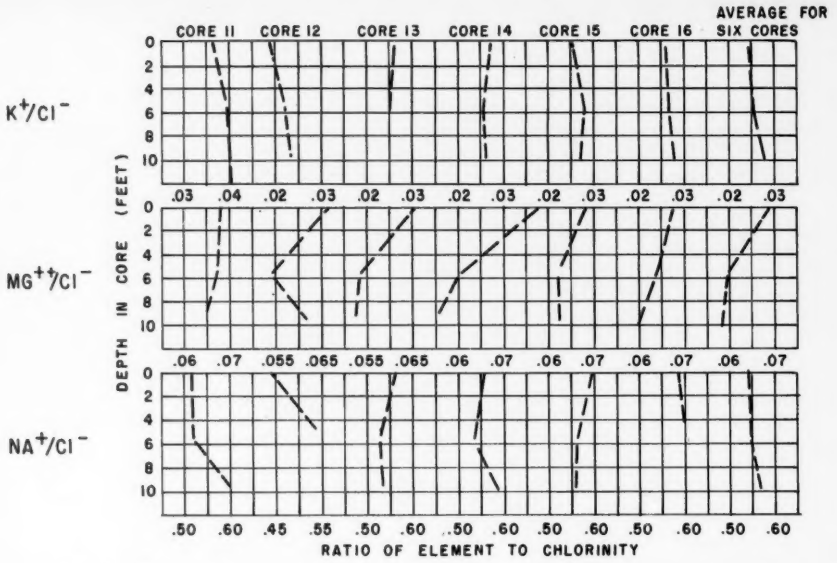


FIG. 3.—Curves of K^+/Cl^-, Mg^{2+}/Cl^-, and Na^+/Cl^- in interstitial water as a function of depth in James Estuary cores.

low as it is squeezed out of the sediment.

If all of the water in the sediments were escaping in a vertical direction, the effect would be to smooth out the concentration curves for the elements in the interstitial water with respect to depth. This smoothing out of concentration curves is indeed not the case for potassium and magnesium (fig. 3), and is evidence against the idea that the water moves out in a vertical direction.

Emery and Rittenberg (1952) in their study of California basin sediments, point out that compaction of muds flushes the interstitial water upward and in the process transfers certain properties to higher levels. This may be true for extensive lateral or blanket deposits of mud, but it does not follow for estuarine muds. In the estuary the mud occurs in the channels and is almost always bounded laterally and below by permeable sand or gravel. The sand and gravel may be thought of as acting somewhat like a blotter for water in the mud, in that it offers a nearby escape for laterally moving interstitial water. The migration of hydrocarbons from thick shale source rocks may show a similar mode of escape.

Chlorine, sodium, calcium, potassium, and magnesium were determined in the interstitial water (table 4). Chloride ion concentration showed only slight changes with depth in the cores (fig. 4). The chloride ion does not enter into any crystalline structure in the sediments studied, and any changes in its concentration with depth would very probably be the reflection of salinity changes in the overlying water at the time of deposition of the sediment column. It seems likely that the environment of deposition has not changed very much during deposition of the sediments concerned.

Figure 3 shows that magnesium generally decreases slightly in the interstitial water with depth in each core. This decrease is very likely because of the adsorption of octahedrally coordinated magnesium on the (00*l*) surfaces of the diagenic chlorite.

Potassium generally shows a slight increase in the interstitial water with depth (table 4 and fig. 3). This increase suggests the desorption of potassium from the clays.

Calcium and sodium in the interstitial water do not show any regular trend of change of concentration with depth (table 4 and fig. 3). These elements are neither desorbed nor adsorbed in any regular fashion

TABLE 4.—*Chemical analyses of interstitial water samples*

Depth in core (feet)	Core 11		Core 12		Core 13		Core 14		Core 15		Core 16	
	Cl− (0/00)	Na+ (PPM)	Cl− (0/00)	Na+ (PPM)	Cl− (0/00)	Na+ (PPM)	Cl− (0/00)	Na+ (PPM)	Cl− (0/00)	Na+ (PPM)	Cl− (0/00)	Na+ (PPM)
0–½	0.84	431	5.37	2340	6.21	3491	10.68	5984	13.70	8160	15.42	9100
5–5½	1.35	702	4.73	2610	6.57	3491	11.17	5984	13.56	7685	15.07	9100
9–10	1.10	664	4.40	2441	6.52	3491	10.27	5960	13.76	7685	15.41	9100
14½–15	1.01	555										
	K+ (PPM)	Mg+2 (PPM)	K+ (PPM)	Mg+2 (PPM)	K+ (PPM)	Mg+2 (PPM)	K+ (PPM)	Mg+2 (PPM)	K+ (PPM)	Mg+2 (PPM)	K+ (PPM)	Mg+2 (PPM)
0–½	20.2	57.6	105.6	357.1	162.0	409.0	288.0	837.6	357.0	935.0	407.5	1047.6
5–5½	40.2	91.0	103.1	258.0	164.0	353.0	288.0	683.1	384.5	843.4	407.5	967.1
9–10	40.3	83.0	102.0	271.1	165.5	340.0	270.0	564.8	367.5	862.1	440.0	927.7
14½–15	40.5	67.9										
	Ca^{++} (PPM)											
0–½	33.0		163.0		176.0		294.0		388.0		295.0	
5–5½	27.0		164.0		164.0		294.2		388.0		360.0	
9–10			137.0		154.0				395.6			
	Mg/K from Above Data											
0–½	2.85		3.38		2.52		9.91		2.62		2.58	
5–5½	2.26		2.50		2.15		2.37		2.19		2.37	
9–10	2.05		2.65		2.05		2.09		2.34		2.10	

0/00=parts per thousand.

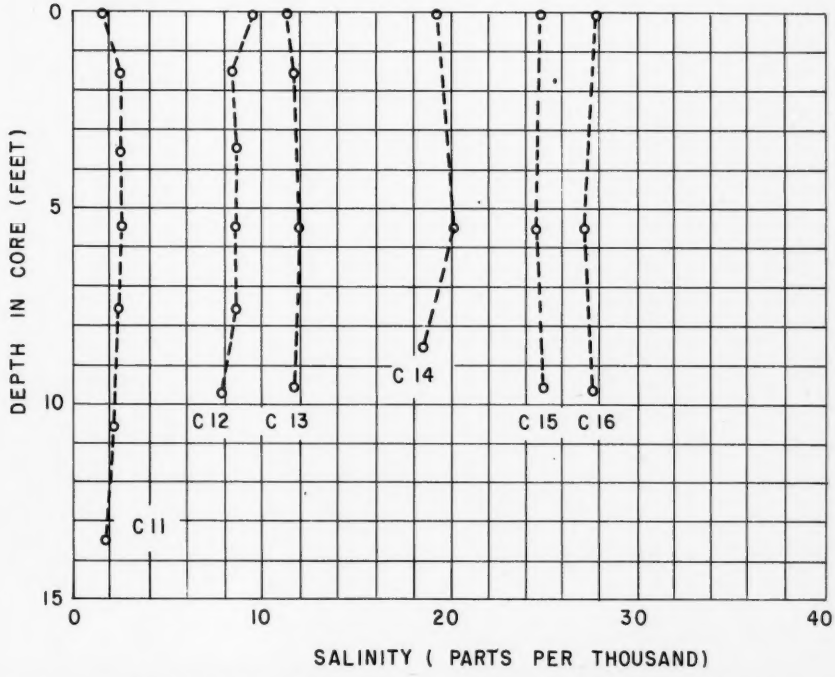


FIG. 4.—Salinity variations in interstitial water from core samples in the James Estuary.

TABLE 5.—*Chemical analysis of HCl-leachate*

Depth in core (feet)	Core 11		Core 12		Core 13		Core 14		Core 15		Core 16	
	K+ (PPM)	Mg+2 (PPM)	K+ (PPM)	Mg+2 (PPM)	K+ (PPM)	Mg+2 (PPM)	K+ (PPM)	Mg+2 (PPM)	K+ (PPM)	Mg+2 (PPM)	K+ (PPM)	Mg+2 (PPM)
0–½	840		1,920		980	8,820	1,820	11,480	2,320	14,780	2,320	15,560
5–5½	1,320	12,040	1,780	12,080	1,360	10,520	2,160	13,520	2,560	15,900	2,520	19,160
9–10	1,220	12,380	1,700	11,380	920	6,500	2,160	10,580	2,520	17,360	2,360	17,580
14½–15	980	10,020										
	Na+ (PPM)	Mg/K	Na+ (PPM)	Mg/K	Na+ (PPM)	Mg/K	Na+ (PPM)	Mg/K	Na+ (PPM)	Mg/K	Na+ (PPM)	Mg/K
0–½	360		1,660		640	9.00	860	6.31	2,200	6.36	1,340	6.70
5–5½	2,040	9.10	1,640	6.79	1,100	7.74	1,880	6.26	1,760	6.21	1,160	7.60
9–10	2,280	10.10	1,800	6.70	820	7.07	2,060	4.89	680	6.89	1,400	7.45
14½–15	1,320	10.20										

by the clays following deposition.

The effect of the biological element on the chemistry of the interstitial water was not determined, but it is not likely that they would have other than a very minor effect on the elements studied. The bacterial influence, however, on sulphur, phosphate, and nitrogen might be considerable. The bacteria might also affect the pH and oxidation-reduction potential of the sediments, and thereby influence certain chemical reactions with regard to the clays.

Hydrochloric Acid Leachate

No sharp line can be drawn between the exchangeable and nonexchangeable ions in poorly crystallized clays such as are found in an estuary. One can only determine the desorbed ions for a given leaching medium for a given time interval. For this work the clays were leached for one hour with 1.0N HCl. This method allows one to determine the relative abundances of "available" ions for depth in cores and position in the estuary. Table 5 gives the data on Mg^{2+}, K^{+}, and Na^{+}. There was no general increase or decrease in magnesium, potassium, or sodium for depth in the sediments or position in the estuary, indicating that the amount "available" is neither a function of salinity or time.

The ratios of magnesium to potassium in the interstitial water and HCl leachate are shown in Table 6. The theoretical ratio of magnesium to potassium for normal sea water is 3.34 and the ratios within the estuary do not vary appreciably from this figure. The range of 2.21 to 2.76 for the interstitial water and 7.10 to 7.28 for the HCl leachate suggests strongly that magnesium is adsorbed by the clays preferentially to potassium. This observation supports the hypothesis that diagenic chlorite is forming in the James Estuary.

Fused Samples

The residue from HCl leaching was washed, dried, and fused. The magnesium and potassium in these samples represents that part which is held in the crystals more strongly relative to the "available" elements and may be referred to as the "unavailable" fraction. Table 7 shows the "unavailable" potassium and magnesium in six fused samples.

Figure 5 is a plot, based on a limited number of samples, of the magnesium-to-potassium ratio as a function of salinity. This graph suggests that somewhere between salinity values of 8.0 and 10.0 parts per thousand, magnesium becomes more abundant than potassium. With increasing salinity, magnesium becomes decidedly more abundant relative to potassium.

Figure 6 shows that the magnesium in the fused samples increases exponentially with relation to the magnesium and chloride in the interstitial water. The exponential relation may be explained in the following way. The octahedrally coordinated interlayer magnesium islands that formed earlier continue to grow while the clays are in suspen-

TABLE 6.—*Ratio of Mg/K in interstitial water and HCl-leachate**

Depth in core	Interstitial water (Mg/K)	HCl-leachate (Mg/K)
0–½	2.76	7.10
5–5½	2.30	7.28
9–10	2.21	7.20

* Average data from six cores.
Mg/K ratio in normal sea water is 3.34.

TABLE 7.—*Chemical analyses of fused core samples*

Depth in core (feet)	Core 11		Core 12		Core 13		Core 16	
	K+ (PPM)	Mg+2 (PPM)	K+ (PPM)	Mg+2 (PPM)	K+ (PPM)	Mg+2 (PPM)	K+ (PPM)	Mg+2 (PPM)
0–½	2,900	95					470	31,830
9–10	1,250	728	2,100	1,512	1,250	3,862	1,700	39,710

sion, tying up magnesium in the interlayer positions; as salinity increases, the more difficultly replaceable potassium in the partially degraded illite is exchanged for magnesium. In this way the surfaces which are potential adsorption sites for magnesium are increased in a downstream direction. The combined effect is to increase the uptake of Mg^{2+} as shown in figure 5.

The relations shown by figures 4 and 5 offer good evidence that a chlorite is forming in the James Estuary. The observation by the author that Mg^{2+} is adsorbed on clays to a greater extent than K^+ in Recent sedi-

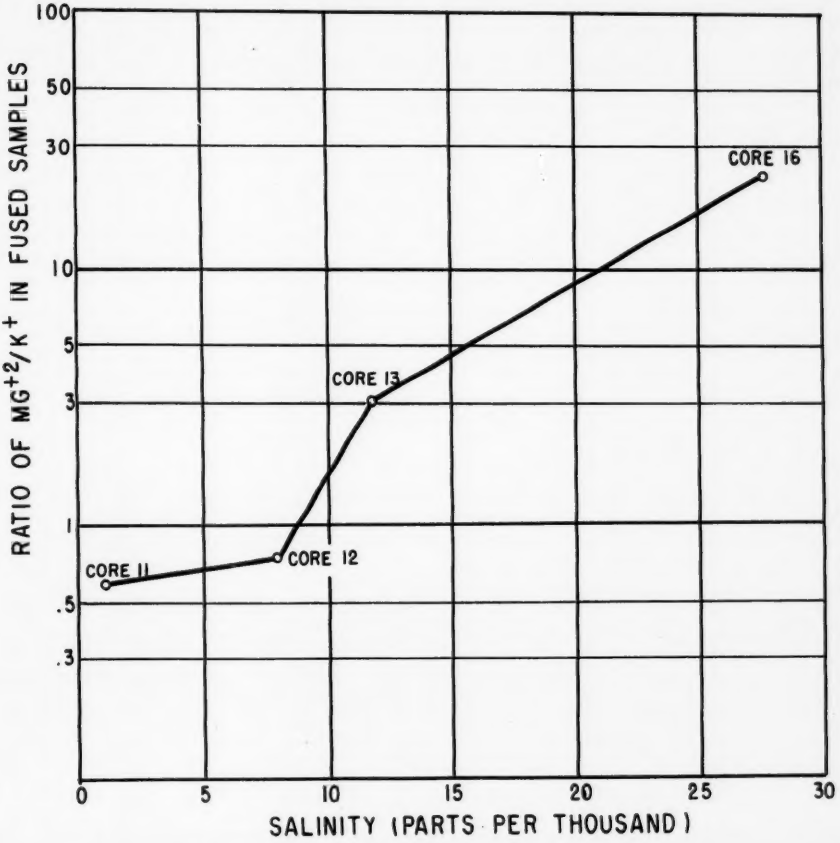


FIG. 5.—Relation of Mg^{2+}/K^+ in fused samples to salinity of interstitial water.

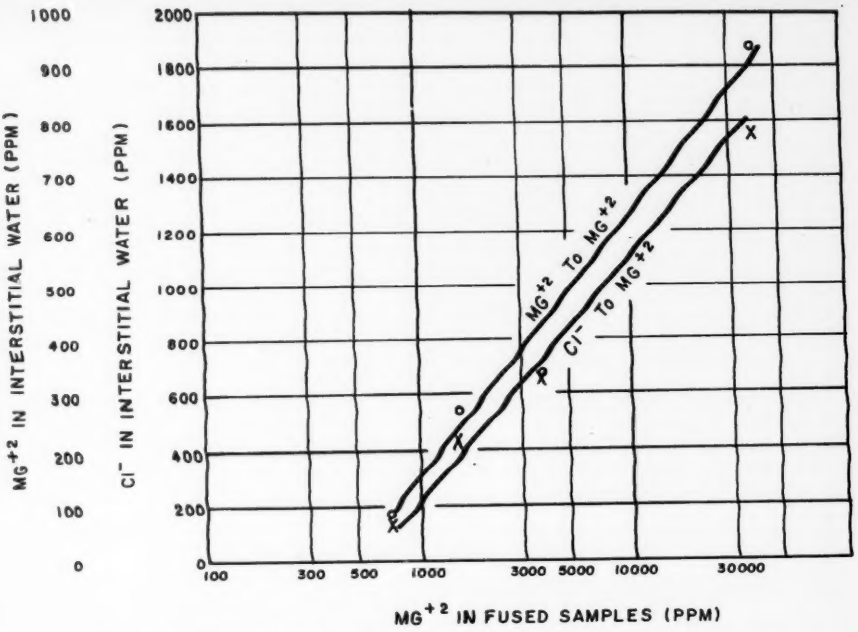


FIG. 6.—Relation of Mg^{2+} in fused samples to Mg^{2+} and Cl^- in interstitial water.

ments of a brackish and marine environment is difficult to refute; other actual observations on field samples bear out this point (Grim and Johns, 1953b, table 2). Regardless of the fact that K^+ has a lower hydration capacity, because of its lower ionic potential, than Mg^{2+} one cannot justifiably say that K^+ is preferentially absorbed with regard to Mg^{2+} in sea water, because the theory does not correctly fit the observations. On the other hand, a possible explanation of the cation adsorption observations lies in the relative concentration of Mg^{2+} and K^+ in sea water. The ratio of Mg^{2+} to K^+ in sea water in numbers of atoms is about 5:1.

Along these same lines, pH is often called upon to account for cation adsorption and diagenesis or authigenesis. The *active* hydrogen ion concentration in fresh and salt water solutions varies within rather narrow limits (pH 5.0–9.0) and, as pointed out by Roy (1953), extremes are rare. Variations of pH within these limits cannot account for the ion exchange phenomena and diagenesis as called on so often in the clay mineralogical literature. In this connection it should also be mentioned that the oxidation-reduction potential in the marine environment probably carries much less importance in the diagenesis of clays than generally thought. The environment of the continental shelves is not always a reducing one. Probably most of the continental shelf along the Atlantic Coast south of Delaware Bay is an oxidizing environment. On the other hand, some of the California basin sediments and Gulf of Mexico sediments are deposited in a reducing environment. The oxidation-reduction potential is sometimes negative at the surface of the California basin sediments and normally decreases with depth (Emery and Rittenberg, 1952). A comparison of a limited number of samples from the three areas shows that diagenesis of the clays proceeds in the same direction regardless of differences in the hydrogen ion concentration and oxidation potential of the depositional environment.

Semiquantitative data suggest that iron

is adsorbed by the clays in an "unavailable" form in the James Estuary. The adsorption of ferrous iron into the octahedral layer of three-layered clay crystals or of ferric iron into the tetrahedral layers would set up an excess negative charge on the crystals that might enhance the adsorption of magnesium which would precipitate as a brucite structure. In this way the iron would act somewhat as a catalyst to the magnesium adsorption reaction. The possibility must be considered that iron may be essential, in some yet unknown way, to the formation of diagenic chlorite. The iron may act as a conditioning agent before or after the clays reach the saline environment. In this connection it should be pointed out that where chlorite has been formed by the author in the laboratory, it was done so from iron-bearing clays. An iron-free A.P.I. bentonite was soaked for about one year in normal sea water without effecting the formation of any chlorite. The role of iron in diagenesis of clays certainly deserves more attention than it has been given in this study.

Depth Factor in Diagenesis and Geochemistry

We may speculate logically as to the role of Mg^{2+} and K^+ and the diagenesis of clay minerals relative to increasing depth of burial. Published analyses of both ancient and Recent shales (Murray, 1953, Grim, 1953, and Powers, 1953) suggests some important geochemical processes as regards the history of marine and brackish shales. It has been stated earlier that Mg^{2+} is adsorbed preferentially to K^+, and the 5:1 ratio of Mg^{2+} to K^+ in sea water has been given to account for this adsorption preference. In this way we can account for the diagenesis of chlorite and illite in brackish and marine sediments. That is, even though the ionic potential of K^+ is less than Mg^{2+}, the latter would be adsorbed preferentially as long as the ratio of Mg^{2+}/K^+ was in the vicinity of 5:1. This does not mean that K^+ would not be adsorbed onto the clays, but that the rate would be less than if the concentrations were equivalent. In equivalent concentrations K^+ would be adsorbed preferentially to Mg^{2+}.

Reasoning as above in terms of ionic potentials and equivalence, we can recognize that the *preferential* adsorption of Mg^{2+} for K^+ with depth cannot continue beyond a certain concentration ratio of Mg^{2+}/K^+. In other words, the Mg^{2+} will have a greater likelihood of being adsorbed the nearer to the surface of the sediment, and the K^+ will gain in its adsorption potential with depth (fig. 7). The depth of the *equivalence level* will depend principally upon the difference in the ionic potential of the two ions and should not exceed a very few hundred feet in any case. Naturally, the physical properties of the sediment, such as compaction characteristics, will play an important part in determining the equivalence level.

Below the equivalence level, one of two possibilities seem likely:

1.—The Mg^{2+} (and iron) may move into the octahedral layer of the lattice and replace Al^{3+} which moves into the tetrahedral layer. The former sites of Mg^{2+} (and iron) would be replaced by K^+. The depth of this reaction would probably be considerable. This reaction would mean that little or no Mg^{2+} would be lost from the clays as they were compacted into shales and slates. It would mean that the amount of K^+ should show a slight overall increase and Al^{3+} should show a slight increase relative to Si^{4+} as the muds were compacted into tight shales and slates. An increase in illite relative to the other clay minerals would result, and the mineral outcome would probably consist of the unaltered clay fraction plus reconstituted, diagenetic, and low-rank metamorphic illite, mixed-layer complexes involving illite, chlorite, and montmorillonoid, and minor chloritic clay. The nature of the mixed-layer clays would depend largely upon the source material. The significance of an increase in illite is related to its predominance in ancient sediments, whereas, chlorite is rarely the dominant clay in ancient sedimentary rocks (Weaver, 1956).

2.—The other possibility of change with depth involves a slow but persistent replacement of Mg^{2+} by K^+. This reaction would occur at a shallower depth than in the above possibility and would be related to a statistical loss of Mg^{2+} from the system. Once K^+ is adsorbed onto the clay surfaces, it would be more difficult to replace than Mg^{2+}, because of its lower ionic potential. In this way some of the more loosely held Mg^{2+} would be "out-maneuvered" by the K^+, resulting in an illite, illite-chlorite, chlorite set of clay minerals.

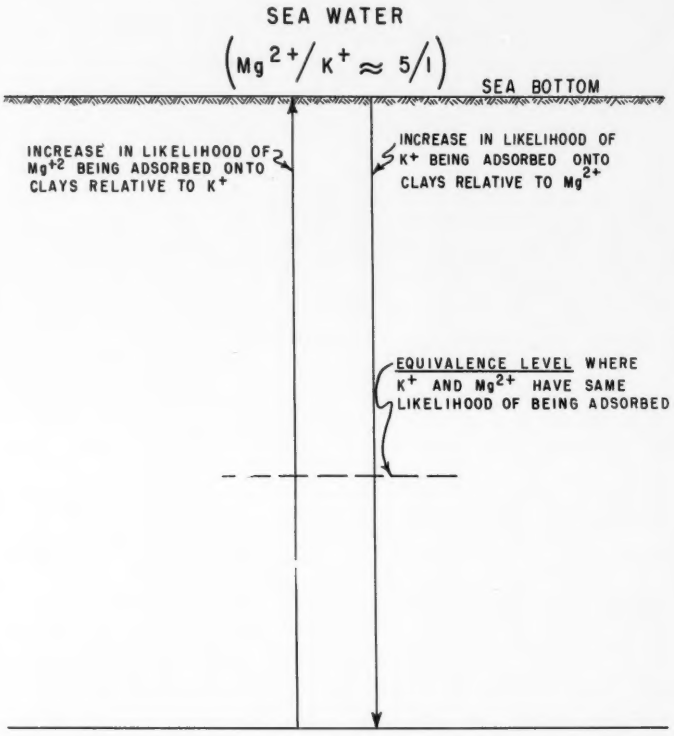

SEA WATER
$(Mg^{2+}/K^{+} \approx 5/1)$
SEA BOTTOM
INCREASE IN LIKELIHOOD OF Mg^{+2} BEING ADSORBED ONTO CLAYS RELATIVE TO K^{+}
INCREASE IN LIKELIHOOD OF K^{+} BEING ADSORBED ONTO CLAYS RELATIVE TO Mg^{2+}
EQUIVALENCE LEVEL WHERE K^{+} AND Mg^{2+} HAVE SAME LIKELIHOOD OF BEING ADSORBED

FIG. 7.—Equivalence level of Mg^{2+} and K^{+}.

Another possibility is that there would be essentially no change after the clays are deposited. This is probably the most unlikely of the possibilities.

Organic Carbon

The organic carbon in the Chespeake Bay muds is extremely complex and probably contains a variety of bituminous and carbonaceous fractions. Qualitative tests on Chesapeake Bay muds reveal the presence of waxes, resins, and hydrocarbons. Thin layers of peat are present, but very uncommon.

A dry combustion method of analysis was used to determine the total organic carbon in about one hundred samples. The maximum organic carbon for the samples investigated was 4.07 percent by weight of dry sample. Most of the dark gray to black muds contained on the order of 0.10 to 1.00 percent organic carbon. The amount of carbon generally decreased to a depth of about 2 feet and then leveled off to a maximum measured depth of 35 feet for one core.

It is quite possible that organic molecules are adsorbed by the estuarine clays while in suspension or following deposition (Sokoloff, 1952, personal communication). Once adsorbed, the organic molecules would probably be fairly stable and difficult to replace. In this way magnesium may be excluded from adsorption by some of the clay, and three-layered clays that otherwise would adsorb magnesium to form chlorite could be preserved without mineralogical change. The adsorption of organics by clays might explain the occurrence of montmorillonoids

in deep sea sediments, as well as the possibility of the accumulation of hydrocarbons in marine clays (Smith, 1954).

DIAGENETIC VERSUS DETRITAL ORIGIN OF CLAY

Millot (1953) discussed the relative importance of "transfer" (detrital) versus "neoformation" (diagenesis) of clays in the marine environment. He concludes that transfer and neoformation may compete with each other, join each other, or operate alone. He points out also the importance of biological phenomena, thus recognizing the three important petrogenetic processes: detrital, chemical, and biological.

The question of the relative concentrations of the detrital clay fraction versus the diagenetic fraction in the final sedimentary accumulation is difficult to answer even for the restricted area of Chesapeake Bay. It is certainly apparent that diagenic chlorite is a very major constituent of the near surface sediments studied. On the other hand, the detrital fraction (illite plus kaolinite) slightly outweighs the diagenetic fraction. In view of the shallow sampling depth in the areas studied (about 10 feet average depth), it is obviously somewhat speculative to extrapolate data of this sort to ancient sediments which may have been buried to great depths, leached by solutions, or otherwise exposed to changing conditions of physics and chemistry. The mere presence of clays in shales rather than in more permeable sandstones does not at all preclude the possibility of diagenesis. The problem is further complicated when one considers that diagenesis of clays will almost surely vary quantitatively from one depositional basin or area to another. It would seem to the author that the diagenetic clay fraction may often exceed the detrital clay fraction in view of observations in the Chesapeake Bay area and in the Atchafalaya area. This problem cannot be solved by studying either Recent or ancient sediments alone; or for that matter, both ancient and Recent unless a continuous time-depth sampling program is undertaken.

SUMMARY

A diagenic chlorite occurs in the estuarine and marine environment and seems to form by the precipitation of octahedrally coordinated magnesium as islands on the basal surfaces of these layered clays. These islands grow along the basal surfaces in response to salinity increase and to a less extent time. Development of the interlayer structure enhances the chemical and thermal stability of the chlorite.

There is no detectable change in the amount or nature of kaolin from the fresh to the salt water environment. Weathered or degraded illite and montmorillonoid decrease in a seaward direction through the estuary as a result of their alteration to diagenic chlorite. Well-formed illite shows only slight to no change in concentration through the estuary.

The occurrence of mixed-layer vermiculitic clays is discussed and given as a possible stage in the development of diagenic chlorite.

It is the author's opinion that the question of the relative importance of the detrital versus the diagenetic fraction of clays must consider post-depositional changes in the clays at relatively shallow depths. In terms of relative abundance of the diagenetic clay minerals, illite is probably the most important end member.

Under a set of ideal conditions, thermal stability of chlorite might be used to give an approximation of the salinity of overlying water at the time of deposition of the sediment. Detrital metamorphic chlorite or postdepositional diagenetic and metamorphic influences would probably rule out such a possibility. Millot (1949) and Siever (1953) have recognized chlorite in ancient sediments. More detailed studies of ancient marine and estuarine clays is needed to determine the potential value of using the chlorite mineral to locate ancient shorelines and to determine environments of deposition.

ACKNOWLEDGMENTS

The writer is grateful to the Chesapeake Bay Institute for supplying grab, core, and water samples from the Chesapeake Bay area. Dr. C. E. Weaver and Dr. R. A. Rowland carefully read the manuscript and made many constructive criticisms. Dr. Rowland kindly heat-oscillated several of the author's samples with his special equipment.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 4, PP. 373–377
FIG. 1, DECEMBER, 1957

CRITERIA USED FOR DISTINGUISHING LACUSTRINE AND FLUVIAL SEDIMENTS IN TERTIARY BEDS OF UINTA BASIN, UTAH[1]

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ABSTRACT

Lacustrine and fluvial Tertiary sediments of the Uinta Basin, Utah differ markedly in many primary respects, and display features which may be diagnostic of the principal environment in which they were formed.

The fluvial and lacustrine sandstones are similar in mass properties, differing primarily in that lacustrine sands are more uniform in appearance than fluvial sands. The lacustrine shales are denser, harder, better bedded, more continuous, somewhat thicker, and contain considerably more of the carbonates, limestone and dolomite, than the fluvial shales. Many limestone and dolomite types (coquinoid, coquinal, algal, and calcarenites, and more common varieties of bedded limestone and dolomite) are found in the lacustrine sediments, but only thin "fluvial" limestone beds are present in the Tertiary rocks of the Uinta Basin.

Final conclusions, applicable to a large number of separate continental deposits, are not drawn because studies of this type are still very much in the "gathering stage."

INTRODUCTION

Continental sediments exceeding 13,000 feet in thickness are found in the Uinta Basin, Utah. Most of these rocks are contained in the lower Tertiary formations as follows: Wasatch (Paleocene-Eocene), Green River (Eocene), Uinta (Eocene), and Duchesne River (Eocene). Other Tertiary continental deposits include the Currant Creek (Paleocene-Eocene) Formation, the Bishop (Oligocene-Miocene?) Conglomerate, and minor beds of undifferentiated Pleistocene. Collectively, these units present an unrivaled opportuntiy for study of lacustrine and fluvial sediments.

The following comments are published in the belief that they may possess more than local significance in establishing reliable criteria for the separation and characterization of sediments deposited in lacustrine and fluvial environments.

SCOPE

The observations presented are largely the result of examination of well samples with the binocular microscope, and are confined to the Wasatch, Green River, Uinta, and Duchesne River Formations. The reader is referred to Bradley (1931) and Dane (1954) for discussions of surface exposures.

CONGLOMERATES AND BRECCIAS

There are very few conglomerates and breccias in the subsurface Tertiary lacustrine rocks of the Uinta Basin. It is probable that many of those that are originally present are "lost" and become indistinguishable through the grinding action of the drill bits.

An interesting and generaly typical lacustrine microconglomerate, found in the interval 3490–3500 feet, was noted in Sun Oil Company's, South Ouray Unit No. 1 (sec. 22, T. 9 S., R. 20 E.). This rock can be described as a brownish gray, argillaceous, edgewise, dolomite conglomerate. The cementing agent is calcium carbonate and the matrix contains unusual quantities of white gypsum (?) crystals. Dolomite and limestone micro-conglomerates appear to be more abundant than other types in the lacustrine sediments. They are often cherty, oolitic, ostracodal, and argillaceous.

In the subsurface, conglomerates and breccias are somewhat more abundant in the fluvial than in the lacustrine rocks. However, they are not as prevalent in well samples as they are in outcrops, especially in the Uinta and Duchesne River Formations along the northern edge of the Uinta Basin.

The fluivial conglomerates are predominantly polymictic and generally poorly sorted. Calcite and clay are the two most important bonding agents.

SANDSTONES

Sandstones, deposited under continental conditions, retain to a great degree the

[1] Manuscript received November 28, 1956.

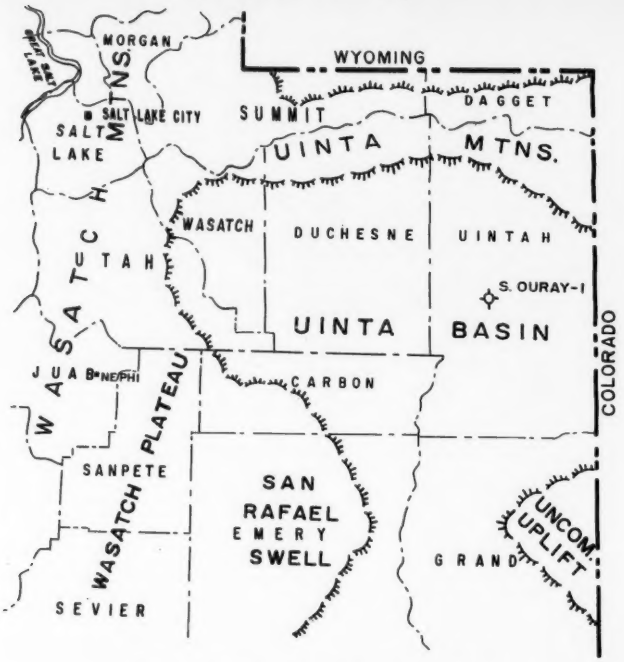

FIG. 1.—Index map of Uinta Basin, Utah.

characteristics of their source beds and are apt to reflect their origin to a greater extent than they are the impact of the depositional environment. This factor makes it difficult to discern peculiar traits that are characteristics of either the lacustrine, or the fluvial environment.

Lacustrine sands are exposed for a longer period than fluvial sands to the effects of running water; that is, they are subject not only to the original stream effect but also to the movement of waves and currents along the lake shore after their initial deposition from the streams. This longer period of activity tends to "even out" or average the range of differences in the lacustrine sandstones and to give them a more uniform appearance than is found in their close relatives, the fluvial sandstones.

According to the Pettijohn (1949) classification the Tertiary sandstones of the Uinta Basin belong to the low orthoquartzite, high subgraywacke, and arkose groups. The most common lacustrine sandstone has approximately the following composition: 70–90% quartz, 5–25% clayey material, 0–10% feldspar, mica, and chert, and 0–5% rock fragments. A sandstone of this composition falls in the upper limits of the subgraywackes (Pettijohn, 1949, p. 256) and the lower limits of the orthoquartzites. The fluvial sandstones tend to contain less quartz and more clay, feldspar, mica, and rock fragments than the lacustrine sandstones. The arkoses of the two groups are found primarily in the upper part of the saline facies, the sandstone and limestone facies, and in fluvial sediments equivalent in age to the two aforementioned units of the lower Uinta Formation. They were derived (Picard, 1955) from granitic terrane exposed east of the Uinta basin in central Colorado.

Red is a common color in fluvial sandstones, but seldom occurs in lacustrine sandstones, at least in those deposited a few tens of yards from the lake shore. However, red sandstones are found in rocks deposited in that portion of the continental environment that fluctuates rapidly between lacustrine and fluvial conditions. In such an environment, the sandstones, if exposed for

any moderate period of time to lake shore action become characteristically lacustrine in appearance; if exposed but briefly, they may be closely akin to fluvial sandstones.

Ostracods and oolites are often found associated with lacustrine sandstones; rarely if ever, are they found as part of definitely fluvial sandstones.

Frosted quartz grains are not common in either lacustrine or fluvial sandstones.

Some other characteristics of the two sandstone types are summarized in table 1.

SHALES

In general the lacustrine shales of the Green River and lower Uinta Formations were formed under conditions primarily chemical; that is, the structural and topographic relief was low in source areas and tectonic activity was slight. They, therefore, contain more than ordinary amounts of the carbonates, limestone and dolomite, and only very negligible quantities of silt (1/256 to 1/16 mm) size particles. Undisturbed varves are common in many lacustrine shales (especially the oil shales) and there is an almost complete absence of discrete coarse clastic particles (>1/16 mm) within the shale beds. In contrast, the fluvial shales are somewhat silt-richer and often contain coarser clastic materials.

Black shales are common in the lowermost part of the Green River Formation (black shale facies) in the subsurface. These lacustrine shales are rich in organic matter and, as might be expected, iron sulfide (both pyrite and marcasite) is a common constituent. Calcium carbonate is high in the black shales and thin laminations can often be seen. The fauna is not a typical black shale fauna (Pettijohn, 1949, p. 288) in that it contains forms which were largely benthonic (gastropods, pelecypods, and ostracods). Coquinoid-like black shales containing many-sized gastropods and pelecypods are quite common as distinct beds in the lower part of the black shale facies.

Siliceous shales are found in lacustrine beds (Evacuation and Parachute Creek Members of the Green River Formation) in close association with ash beds from which they undoubtedly derived their high silica content. This type of shale may be somewhat more common in the lacustrine rocks of the Uinta Basin than has previously been realized.

In many of the lacustrine shales, especially the oil shales and closely related rock types, fissility is poor, and the shales show a subconchoidal fracture. Other lacustrine shales, containing less carbonate or siliceous material, are somewhat more fissile, although probably less so than the average marine shale.

Some of the more easily observed characteristics of the Uinta Basin lacustrine and fluvial shales are summarized in table 2.

TABLE 1.—*Characteristics of Lacustrine and Fluvial Sandstones in Tertiary Sediments of Uinta Basin, Utah*

Character	Lacustrine sandstones	Fluvial sandstones
Class	Low orthoquartzites, high subgraywackes, arkoses	Low orthoquartzites, high subgraywackes, arkoses
Roundness	Most often in subrounded to rounded range. (Subrounded most common)	Most often is subangular to subrounded range
Size	Usually very fine to fine. Siltstones (<16 mm.) are common	Usually very fine to medium. Tend to be larger on the average than lacustrine sandstones. More often range up to coarse-grained
Sorting	Good to excellent	Poor to good
Cementing Agent	1) Calcite, 2) dolomite, 3) silica	1) Calcite. Occasionally clay, or clay and calcite. Only rarely is any other cementing agent present
Other constituents		Rock fragments more common in fluvial sandstones. Often "salt and pepper" in appearance
Color	Most are white to light gray	White to light and medium gray, red, green, and greenish gray
Bedding	Some grading has been observed	Current bedded
Lateral continuity	Usually more continuous than fluvial sandstones	

TABLE 2.—*Characteristics of Lacustrine and Fluvial Shales in Tertiary Sediments of Uinta Basin, Utah*

Character	Lacustrine shales	Fluvial shales
Color	Some shade of brown or gray. Less often some shade of green	Usually some shade of red or green. Occasionally tan, ocher, maroon, or gray
Hardness	Moderately to very hard	Soft to moderately hard
Luster	Subwaxey to resinous. Sometimes earthy	Earthy
Accessory materials	Pyrite, marcasite, chert, silica, and unusual saline minerals	Rock fragments
Cement	Calcite, dolomite, and silica	Calcite
Bedding	Thinly bedded and varved	Seldom pronounced
Lateral continuity	Usually much more continuous than fluvial shales	
Bed thickness	On the average, somewhat thicker than fluvial shales	

LIMESTONES AND DOLOMITES

All of the limestones and dolomites found in the Tertiary sediments of the Uinta Basin are probably lacustrine in origin in the sense that they were formed, or deposited (in the case of clastic limestones), in standing bodies of water. However, there are certain differences between those much less extensive carbonates found in the predominantly fluvial formations and those found in the predominatly lacustrine stratigraphic units.

The "fluvial" carbonates are entirely limestones. No dolomites have been found. In chemical composition, they appear to contain much less foreign material (clay, etc.) which is interpreted to mean that they were deposited in clearer water than the "lacustrine" limestones. The grain size is usually very fine to fine, and the most common colors are light gray, light tan, or rarely pink to light red. Fossils are uncommon in the "fluvial" limestones. In lateral continuity individual "fluvial" limestone beds are less continuous than "lacustrine" beds, and the average thickness is also generally less.

The most common lacustrine limestones are crystalline or chalky, argillaceous, siliceous (?) types. They are found throughout the Green River and lower Uinta Formations and are light gray, tan, medium or dark brown in color. The grain size ordinarily falls in the medium to very fine range, and many beds are thinly laminated (Picard, 1955).

Of the autochthonous limestones, a coquinoid type, containing, for the most part, benthonic forms (gastropods and pelecypods), is common in the lacustrine sediments of the Green River Formation in the Uinta Basin. Ostracodal limestones, many of which are oolitic, are also abundant in lacustrine rocks. Most of the ostracodal and coquinoid limestones are brown or gray in color, and contain considerable argillaceous material. The grain size varies from very fine to large.

Coquinas and microcoquinas—distinguished by pronounced fragmental character of the shell debris—are common in the lacustrine Green River Formation.

Calcarenites, other than oolitic limestones, are often found in the lacustrine rocks of the Green River and lower Uinta Formations in direct association with orthoquartzitic sands. In such limestones, quartz sand grains (usually well rounded) are common to abundant and they often grade into very calcareous sandstones. Normally, however, they do not appear to form every gradation between the two, and the calcarenites are easily separated by percentage composition from the calcitic orthoquartzites.

Algal limestones occur in some areas, especially in surface exposures, and have been described by Bradley (1929). These limestones are difficult to detect in well samples but they have been recognized.

Dolomites are most extensive, in both total volume and lateral extent, in the Parachute and Evacuation Creek Members of the Green River Formation. Here they are formed in intimate mixture with calcite, clay, silica, and organic material; and are called dolomites when that carbonate member is predominant over the other com-

TABLE 3.—*Characteristics of lacustrine and fluvial carbonates in Tertiary sediments of Uinta Basin, Utah*

Character	Lacustrine limestones	Fluvial limestones
Autochthonous types	Coquinoid and algal	
Allochthonous types	Calcarenites, calcirudites, calcilutites, coquinas	
Chemical limestones	Bedded varieties very common	"fresh-water limestones"
Color	Most are gray, tan, brown	Tend to be somewhat lighter in shade than lacustrine limestones. Sometimes pink, red
Accessory materials	Quartz, clay, marcasite, pyrite, silica (chert)	Clay, quartz
Texture	Crystalline, sucrose, chalky	Usually crystalline
Grain size	Very fine to large	Usually very fine to medium
Fossils	Ostracods, gastropods, pelecypods	Rare
Lateral continuity	Predominantly more continuous than fluvial limestones	
Bed thickness	Usually much thicker than fluvial limestones	
	Lacustrine dolomites	**Fluvial dolomites**
Type (oil shales)	Overwhelmingly predominant is a bedded variety in intimate mixture with clay, calcite, silica, and organic material	Not present
Other types	Some other bedded varieties are present	
Color	Gray, tan, brown, black (?)	
Texture	Most commonly crystalline	
Accessory materials	Marcasite, pyrite, tuff, analcite, silica	
Grain size	Usually very fine to fine	
Fossils	Ostracods common, plant fragments. Many micro-fossils (Bradley, 1931)	

ponents. Ideally, the mineral, dolomite, should constitute 50 percent of the total rock composition.

Commonly the dolomites are medium to dark brown, crystalline, very fine to fine, and thinly laminated (varved). Most are oil shales. Other, less important, occurrences of dolomite are found throughout the Green River and lower Uinta sections.

It seems improbable that the dolomites originated as replacements of original calcitic limestones. They do not exhibit a granoblastic texture and are unusual in that most of them are mixtures of clay, calcite, silica, and organic material. No definite replacement features have been noted by the writer under the binocular microscope, but only a few thin sections have been examined petrographically. It is the writer's belief that they were precipitated at some stage previous to lithification from magnesium-rich lake waters. Some characteristics of the carbonates are summarized in table 3.

ACKNOWLEDGMENT

The encouragement and editorial suggestions of Dr. William Lee Stokes, of the University of Utah, were very helpful in preparation of this paper.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 4, PP. 378–386
FIGS. 1–3, DECEMBER, 1957

SURFICIAL SEDIMENT IN LAKE MEAD[1]

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ABSTRACT

The surficial sediment along a 70-mile reach in Lake Mead was examined as to texture and mineralogical composition in order to determine possible relations to diagenesis and deposition. Samples were taken at six locations from Grand Wash at the upstream end of the lake to the Intake Towers at Hoover Dam. Differences in texture and clay composition were noted between samples upstream and downstream from Virgin Basin. The median diameter of laboratory-deflocculated sediment samples are between 4.2 and 4.6 microns on the downstream side of Virgin Basin and less than 2 microns upstream. Mineralogically, montmorin-type clays dominate the dispersed clay fraction upstream whereas illite is predominant downstream. The quantity of water in Lake Mead represents a calcareous, flocculating environment for responsive clays and it is proposed that particle-size distribution in the native environment is different from the dispersed state, probably due to montmorin-bound flocs existing in the silt-size range in the lake water. An alternative hypothesis for the differential distribution of texture and composition is the possible "drag" exerted on the surface of sediment near the dam by the outflow of water through the gates, resulting in winnowing of the fines from the surficial material.

INTRODUCTION

Lake Mead is the reservoir formed by Hoover Dam on the Colorado River and covers parts of southeastern Nevada and northwestern Arizona. The total storage capacity of the lake was 31,250,000 acre-feet in 1935 and 29,827,000 in 1949, of which 9,500,000 acre-feet has been delegated to flood control. In 1949 the lake was about 80 miles long and 8 miles wide at its largest part, with depths ranging up to 450 feet at high water. The lake consists of alternating wide and narrow segments, described as basins and narrows or canyons (fig. 1).

The water and sediment that enter the lake are derived from a drainage area of about 168,000 square miles. The main contributing stream of both water and sediment is the Colorado River; contributions from the Virgin River are relatively minor. The greater part of the sediment inflow is derived from the Colorado Plateau province in Arizona, Colorado, New Mexico, and Utah. Minor amounts come from the high Rocky Mountain areas in Colorado and from the upper Green River Basin in Wyoming.

The present study is concerned with the surficial or most recent deposits in Lake Mead. The objective was to study the texture and mineralogical characteristics of such material to determine possible depositional processes in such a large basin and to trace the changes, if any, in the transported sediment along a 70-mile reach from Grand Wash to the Intake Towers.

Recent studies of sedimentation in Lake Mead are described in the report by Smith, Vetter, Cummings, and others (1954) and are summarized in the report by Thomas (1954). The former report is extremely detailed with respect to sediment and salinity.

MATERIALS AND METHODS

The surficial sediments examined in the present investigation came from six sampling points in Lake Mead (fig. 1). These points lay along a reach of about 70 river miles from Grand Wash (mile 285.0)[3] to the Intake Towers (mile 354.7). Two of the samples were taken during the April 1952 sampling cruise of the Bureau of Reclamation and the other 10 were taken in April, 1953. The samples were collected in duplicate at each point, an upper one from the water-sediment interface and a lower one from directly beneath, in the sediment body. The two 1952 samples were used to fill in shortages in the 1953 sampling and represented interface conditions (or upper zones) in both cases. Details of the sampling in

[1] Publication approved by the Director, U. S. Geological Survey. Manuscript received August 14, 1956.

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[3] River miles are measured from an initial point at Lees Ferry, Arizona, the demarkation of the lower limit of the upper basin of the Colorado River as established by the Colorado River Compact of 1922.

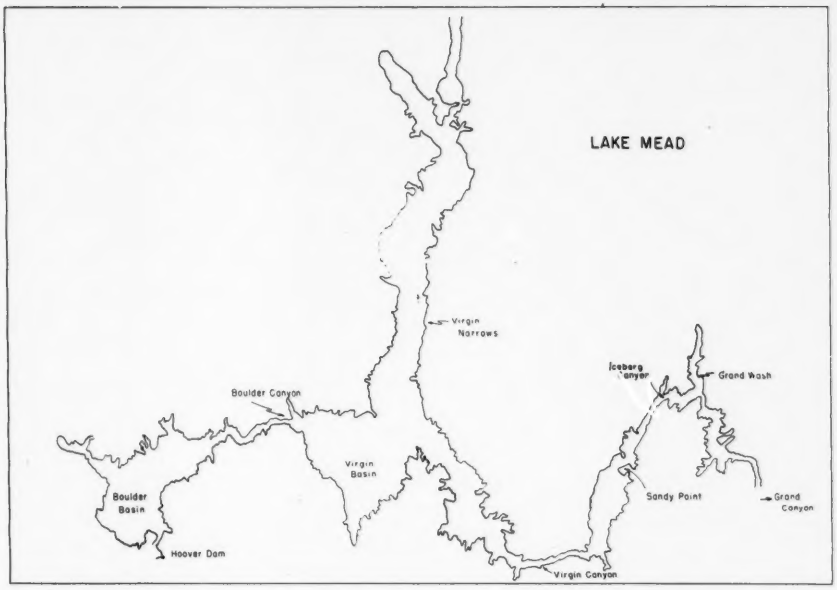

FIG. 1.

Lake Mead are presented in table 1. The modified Foerst sampler used during the cruises by the Bureau of Reclamation is fully described in the report by Smith, Vetter, Cummings, and others (1954).

The sediment samples were analyzed in the Geological Survey soil research laboratory at Denver, where pH, particle-size distribution, and mineralogy were determined. The pH was determined for the untreated native sediment slurry with a Beckman glass electrode pH meter. Texture or particle-size distribution was determined by a modification of the method described by Truog and others (1936), using sodium tripolyphosphate as a deflocculating agent. The mineralogy of the native bulk samples and of the size fractions 20-2 microns, 2-0.8

TABLE 1.—*Sampling data, Lake Mead*

Sample number	Date taken	Location	River mile	Depth from water surface (feet)	Elevation above mean sea level (feet)
1	Apr. 29, 1953	Intake Towers	354.7	421.5	727.25
2	Apr. 29, 1953	Intake Towers	354.7	425.0	723.75
3	Apr. 13, 1953	Boulder Canyon	334.0	391.0	759.95
4	Apr. 13, 1953	Boulder Canyon	334.0	396.0	754.95
5	Apr. 14, 1953	Virgin Canyon	305.0	305.0	845.83
6	Apr. 14, 1953	Virgin Canyon	305.0	306.0	844.83
7	Apr. 15, 1953	Sandy Point	293.5	220.0	930.70
8	Apr. 1, 1952	Sandy Point	293.5	216.0	918.00
9	Apr. 15, 1953	Iceberg Canyon	287.5	160.0	990.70
10	Apr. 15, 1953	Iceberg Canyon	287.5	161.0	989.70
11	Apr. 14, 1953	Grand Wash	285.0	132.0	1018.70
12	Apr. 1, 1952	Grand Wash	285.0	126.0	1007.89

TABLE 2.—*pH of the untreated samples, Lake Mead*

Sample number	pH
1	7.0
2	7.2
3	7.5
4	7.3
5	7.6
6	7.2
7	7.3
8	7.0
9	7.3
10	7.6
11	7.1
12	7.5

microns, and less than 0.8 microns was determined by means of X-ray diffraction (Fe Kα radiation with Mn filter) and ethylene glycol sorption.

RESULTS AND DISCUSSION

pH Determinations

The results of the pH determinations of the unmodified natural sediment slurries are shown in table 2.

The determinations indicate that there is no significant difference in pH among the 12 samples. Although no chemical analyses of the water in Lake Mead were made during the present investigation, previous data on this subject indicate that the composition is calcium-dominated. pH values of 7.0 to 8.3 in such systems are usually associated with a calcareous aqueous medium. A range in pH determinations from 7.0 to 7.6 may be considered normal for such systems. Further work on the implication of the pH values of the 12 samples would require definition of the ternary system, Ca-Na, H_2O, and CO_2.

The samples in the present study are about neutral (pH 7) in reaction and are probably buffered on the alkaline side by calcium salts. There is evidence of little hydrolysis of sodium salts inasmuch as the pH would then be greater, probably above 8.5. It may, therefore, be assumed that the waters of Lake Mead at the time of sampling were calcium-dominated. The relative concentrations of divalent versus monovalent cations are of especial importance with respect to the dispersion characteristics of the suspended sediment. Divalent cations like calcium are conducive to flocculation whereas monovalent cations like sodium are less efficient floculating agents, being usually associated with dispersion. The outstanding feature of the pH determinations is their uniformity, indicating mixing of the waters and a general flocculating environment.

Particle-size Distribution

The sediment samples were dispersed by adding sodium tripolyphosphate to distilled water and were then analyzed as to texture. Figure 2 shows the cumulative size distribution curves for the 12 samples. There are two distinct clusters of curves, one representing samples 1–4 and the other, samples 5–12. The median diameter of the first group lies between 4.2 and 4.6 microns whereas that of the latter is less than 2 microns. Samples 1–4 came from points at the Intake Towers and Boulder Canyon, both of which locations are downstream from Virgin Basin. Samples 5–12 were collected at Virgin Canyon, Sandy Point, Iceberg Canyon, and Grand Wash, all locations being upstream from Virgin Basin. The intriguing feature of these results is the apparent reversal in distribution of sedimentation diameters, in that the finer particles lie upstream from the coarser. Possible explanations for this seeming anomaly will be discussed later. At present, the writer wishes merely to point out that the dispersing environment of a laboratory analysis for particle size distribution is different from that in the calcareous natural waters in Lake Mead. Unfortunately, there was insufficient water in the samples to determine the size distribution of the sediment particles in their natural environment, Lake Mead water. From the pH determinations, we may assume that the natural environment is conducive to flocculation and rapid settling. Other work in the Geological Survey laboratory at Denver indicates that the ternary system, montmorin clay-water-ionized salt, is extremely responsive to changes and that median diameters may shift ten-fold from a dispersing to flocculating environment.[4] Therefore, any difference in content of responsive clay minerals like montmorin would produce significantly different size distribution in dispersed versus natural environments.

[4] Rolfe, B. N.; Miller, R. F.; and McQueen, I. S., *manuscript in preparation.*

MINERALOGICAL ANALYSES

X-ray Diffraction Data

Natural bulk samples.—X-ray diffraction patterns of the natural, unmodified bulk samples were run as oriented, water-dispersed aggregates on microscope slides. The material was slurried in distilled water and allowed to settle. They were then stored in the X-ray laboratory and allowed to come to equilibrium with the room atmosphere. Because of the suspected presence of a montmorin mineral in the sediment, the relative humidity of the laboratory atmosphere was determined for each spectrometer run. Other investigators have shown that the clay mineral, montmorillonite, has a lattice spacing that is responsive both to relative humidity of the environment and to the inorganic cation in exchange position on the clay surface (Brindley, 1951). The relative humidity of the laboratory atmosphere was measured during each spectrometer run by a battery-operated, fan-ventilated, small-model psychrometer. Thus, the probable percentages of exchangeable sodium and calcium in interface position on the montmorin mineral could be roughly estimated. Reference lattice spacings for montmorillonite saturated with various cations and under a widespread percent relative humidity were taken from an article by Hendricks, Nelson, and Alexander (1940). In this way, the need for controlled humidity in the laboratory was avoided and a careful check was maintained easily.

The spectrometer patterns of the bulk samples are sharper than those of the fractionated, treated, size-separates. They indicate the presence of quartz, mica, kaolin, montmorin, calcite, and feldspar. The amounts of kaolin, mica, and quartz do not appear to vary significantly among the 12 sediment samples. Calcite was especially strong in sample one (sediment-water interface at the Intake Towers) but was moderate in all other samples. The feldspar content was erratic in distribution, varying from a trace to moderately low amounts.

The X-ray reflections of the montmorin mineral indicate the presence of both exchangeable calcium and sodium ions. As noted previously, the relative humidity of the X-ray laboratory atmosphere was de-

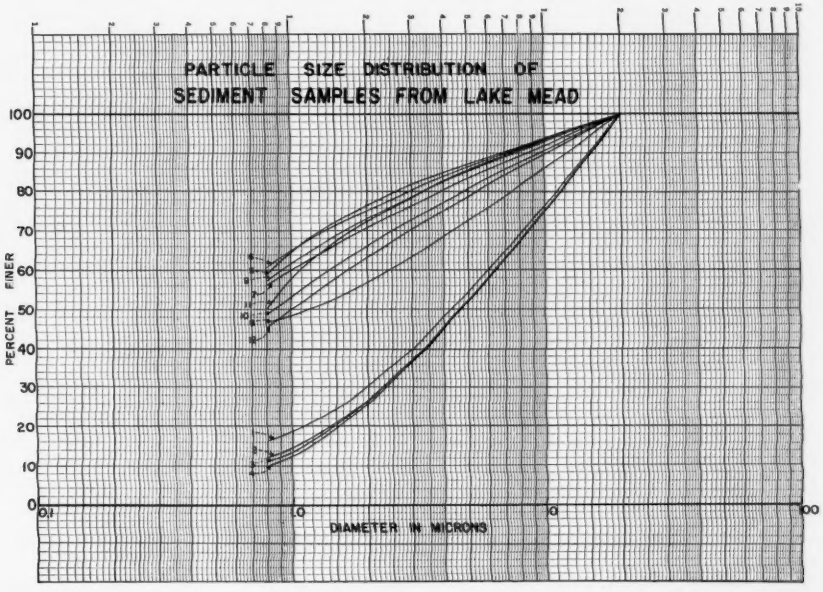

FIG. 2.

termined during each sample run and varied within the limits of 24 to 29.5 percent. The lattice spacings attributable to either calcium or sodium could then be distinguished. It must be noted that a lattice spacing associated with an ion such as sodium merely indicates the clay mineral is exhibiting properties associated with a Na-montmorin. It does not mean that the exchange complex is 100 percent Na-saturated. The same is true of Ca-associated spacings. However, variations in lattice spacings due to different exchangeable inorganic cations like calcium and sodium may be compared on a relative basis to indicate possible dominance by either ion.

At the Intake Towers, there was a clear division of X-ray reflections from clay minerals between those attributable to sodium and to calcium. There were distinct reflections at 10.7 and 13.7 Å, corresponding respectively to reported interplanar spacings for Na- and Ca-montmorillonites at 25 percent relative humidity. In all other samples, the spacings varied between these two end points. Apparently, sodium and calcium montmorillonite particles may exist discretely and as mixed-layer minerals. There was no discernible relation between sampling location and kind of exchangeable ions.

Silt-size (20-2 micron) fraction.—The X-ray diffraction study of the 20-2 micron size fraction was conducted on Mg-saturated, oriented aggregate slides. This was followed by a K-saturated, water-solvated treatment to distinguish among the hydrous micas, vermiculite, and chlorite. The data indicate equal dominance of quartz, kaolin, mica, and hydrous mica in all samples, with no significant difference among samples. Feldspar is present in moderate amount throughout all 12 samples. Calcite is especially strong in sample one and is weak in other samples. Dolomite is weak in sample one and is present in moderately strong amounts in other samples. There are no trends toward differential sedimentation evident in the X-ray study of the silt fractions of the various samples.

Coarse clay-size (2-0.8 micron) fraction.—The X-ray diffraction study of the coarse clay fractions was conducted on Mg-saturated, glycerol-solvated, oriented aggregate slides. This was followed by an analysis of X-ray reflections from K-saturated material, mounted in distilled water as oriented aggregate slides. The dominant minerals throughout were kaolin and a mixture of mica and hydrous mica. A montmorin mineral occurred in moderate amounts in samples 5–10 and calcite appeared in trace amounts in 9–12. Feldspar was present in trace to moderate amounts in all samples.

The X-ray reflections from this size fraction were poorer in clarity than either those of the bulk or of the silt-size fraction. This was true of both the glycerol and K-treated slides. The diffuseness and broadness of peaks was especially evident in the lower angle reflections (10–18 Å), indicating a possible disturbance by dispersion procedure of the maximum basal orientation possible. It is likely that dispersion by a dehydrated sodium phosphate like tripolyphosphate is partially effected by polyanion adsorption to the clay edges. This bond, which aids dispersion by increasing the negative charge of the clay particles, probably persists through washings with distilled water. Subsequent drying may recrystallize the phosphate compound and impede maximum orientation along the basal planes. At any rate, the mineral composition of the coarse clay appears generally uniform, save for the aforementioned calcite and montmorin.

Medium and Fine Clay-size (under 0.8 micron) Fraction.—The treatment of this size fraction was similar to that of the coarse clay. Again, X-ray reflections from the pairs of samples were poor and diffuse. The probable reasons for the poor reflections are the same as were proposed for the coarse clay. The diffractometer patterns indicate the presence of a 10 Å mica and an expandable lattice mineral like montmorin. The analyses of all samples were generally similar and indicated equal proportions of mica and montmorin.

Ethylene Glycol Sorption Data

Martin (1955) has described a replicable technique for characterizing clays according to their ability to sorb ethylene glycol. The milligrams of glycol retained per gram of clay by this method are as follows for some representative (<2 micron) clay minerals: montmorillonite, 280; illite, 70; hydrous mica, 65 to 210; and kaolinite, 15. Previous unpublished work by the writer indicates that the weathering of montmorillonite re-

duces glycol retention probably due to a reduction in charge by the movement of H-displaced Al^{+++} from lattice to exchange position; the reverse is true of mica, weathering increases glycol retention probably by depotassication leading to a form of hydrous mica.

The quantitatively non-definitive nature of the X-ray data for the silt and especially the clay fractions indicated the need for accessory information such as glycol retention. The results of the glycol tests are presented in table 3. Pertinent statistical relations have been included. Examination of the data for the three size fractions in all samples indicate differences only in the finer clay. There was an evidently greater amount of glycol sorbed by samples 5–10 in the <0.8 micron size. However, the data generally revealed no significant differences.

It has been noted that the particle size analysis provided a clear textural distinction between samples 1–4 and 5–12. It was therefore decided to compare these two groups on the basis of glycol retention.

A statistical analysis by means of t tests for the significance of glycol retained by the various size fractions in the two groups of samples is given in table 4. It may be seen from this table that the t values cover a wide range, from 1.19 to 5.35. At the 10 degrees of freedom available for the two groups, only the fine clay sorption data indicate a significant difference between groups. The probability that such a difference could exist by chance alone is less than 1%. The data for the other two size fractions indicate that it is highly probable that the two groups come from the same population. The P value for the silt sorption lies between 5 and 10% and that for the coarser clay is between 10 and 50%. This information, together with the size distribution curves, indicates that the source of difference between the two groups lies in the fine clay fraction.

TABLE 3.—*Milligrams of ethylene glycol sorbed per gram of material*

Sample number	Glycol sorbed		
	20-2μ	2-0.8μ	<0.8μ
1	38.8	111.4	155.4
2	45.1	95.6	150.9
3	32.9	77.7	164.0
4	38.3	82.2	144.5
5	43.7	91.3	188.1
6	57.9	113.4	189.0
7	53.7	108.7	183.9
8	31.8	96.4	183.7
9	48.4	104.6	191.7
10	44.4	107.7	181.2
11	36.3	76.4	161.6
12	47.5	106.9	168.7
$\bar{X}$	42.4	97.7	171.8
S	7.8	13.2	44.5
$S_{\bar{x}}$	2.2	3.82	12.9

The differences between the two groups of samples are probably due to their separation by a large body of water, namely Virgin Basin. There are two possible explanations for the observed results. One lies in the ternary system, montmorin clay—Lake Mead water—ionized calcium salts. The dominant cations are calcium and magnesium, sodium being present in minor amount. This represents a calcareous, flocculating environment for responsive clays like montmorin. The net effect of the interactions in the ternary system is to produce flocs from hitherto small particles, thereby increasing the sedimentation diameter. Rolfe, Miller, and McQueen (in preparation) have shown that the median diameter of montmorin particles may vary from less than 1 micron in a dispersed environment to greater than 15 microns when the environment is flocculent. Therefore, a classic longitudinal section throughout the sediment surface may exist in the natural waters wherein the fines (non-clay minerals) stay in suspension longest and the coarser particles (consisting of flocs of clay) fall out first. Analyses in the deflocculating media used by laboratories may disperse natural flocs, producing a picture of an apparent reversal in normal settling velocities of particles.

As stated earlier, there was not enough water available in the sample containers to determine possible differences in texture between natural and dispersing environments. Gould found (Smith, Vetter, Cummings, and others, 1954, p. 224) that particle-size distribution in natural waters differed sharply from that in a deflocculating medium. He reported that the median diameter of particles from surficial sediment from bottomset beds in Lake Mead (presumably in the downstream portion of the lake) ranged from 11.0 to 13.0 microns in untreated lake

TABLE 4.—*t tests for glycol retained by various size fractions in Group 1 (Nos. 1–4) versus Group 2 (Nos. 5–12)*

	Silt (20-2μ)		Coarse clay (2-0.8μ)		Fine clay (0.8μ)	
	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2
Sample numbers	1–4	5–12	1–4	5–12	1–4	5–12
Degrees of freedom	3	7	3	7	3	7
$\bar{X}$	38.8	48.4	91.7	100.7	153.7	181.0
S (pooled)	4.89		7.59		5.10	
t	1.96		1.19		5.35	

At 10 degrees of freedom, P and t values follow:

P	t
0.50	0.70
.10	1.81
.05	2.23
.02	2.76
.01	3.17

water and from 0.9 to 7.0 microns in a dispersing medium. Sherman (1953) discussed the flocculent structure of suspended sediment in Lake Mead and also noted the difference in size-distribution curves between natural and dispersing environments.

In the present investigation, the median diameters of dispersed samples 1–4 ranged from 4.2–4.6 microns whereas those of samples 5–12 were less than 1.2 microns. The fine montmorin particles would thus have to attain floc sizes greater than about 5 microns in diameter in order to conform to the hypothesis that such coarse particles upstream from Virgin Basin exceeded the suspended sediment downstream in settling velocity. In the light of preceding statements, this is not an unreasonable supposition provided that the particles are dominantly montmorin clay, in a flocculating, calcareous medium, and sufficient time is available for floc growth.

The other possible explanation for the difference between the two groups of samples concerns the influence of the outlet gates. Figure 3 shows the sediment surface as compiled from sampling data. The elevations of this surface at the Intake Towers and in Boulder Canyon are approximately 725 and 755 feet respectively. The outlet gates are located at two elevations, 895 and 1045 feet. The flow net brought about by the opening of the lower gates is believed to be sufficiently extensive to reach the sediment deposits downstream from Virgin Basin e.g., at the Intake Towers and Boulder Canyon. It does not seem likely that the deposits on the upstream side of Virgin Basin would be appreciably affected.

Agitation by the water moving into the outlet gates of the sediment deposits downstream from Virgin Basin probably causes the particles at the affected surface to go into suspension. The fine clay particles would be most susceptible to such agitation; moreover they would remain suspended longer than the coarser particles. Consequently, it is likely that much of the fine material is carried away in the outflowing water. A constant winnowing of fine clay from the sediment surface of the agitated area may take place, resulting in the quantity of fine clay in surficial deposits west of Virgin Basin being less than those upstream

Observers have noted the cloudiness of discharge water from Lake Mead, which indicates that sediment may have been taken into suspension by the outflowing water. This latter hypothesis seems to offer at least a partial explanation of the apparent reversal in sedimentation size distribution. The influence of the ternary system, montmorin clay—Lake Mead water—ionized calcium salts, cannot be overlooked as a possible explanation for the phenomenon.

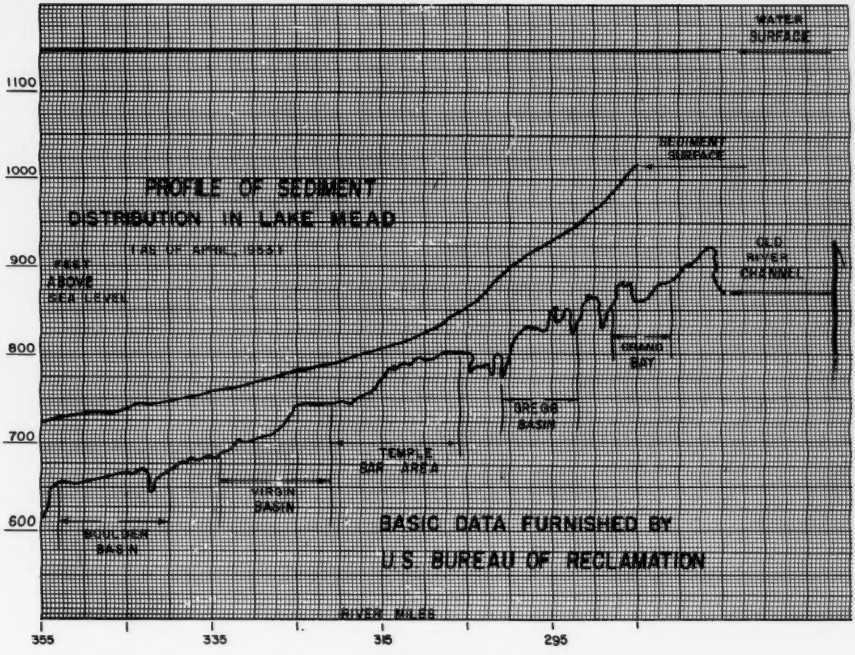

FIG. 3.

SUMMARY AND CONCLUSIONS

The surficial sediment in Lake Mead was sampled at six points between the Intake Towers and Lake Mead. Two samples were taken in April, 1952 and 10 in April, 1953. Mineralogical and textural analyses revealed significant differences between the sediment above and below Virgin Basin. Increase in the median diameter of particles downstream from Virgin Basin was accompanied by a decrease in content of montmorin clay. The pH of the samples was uniform throughout the entire sampled reach, ranging from pH 7.0 to 7.6 indicating the presence of a calcareous medium.

The differences between the groups of samples taken upstream from Virgin Basin and those taken downstream may be attributed either to sedimentation in a natural flocculating environment or to the effect of the drag on the sediment surface exerted by the water flowing toward the outlet gates or to a combination of the two processes. Particle-size analysis of the sediment was effected in the laboratory, using a dehydrated sodium phosphate as deflocculent. This is different from the probable textural composition in the native, calcareous environment. The outlet gates are at an elevation sufficiently close to the sediment surface to produce agitation of the surficial sediment, thereby removing the fine clay. It is likely that floc formation and outflow agitation are both factors in producing the differences between the surficial sediment on the upstream and downstream sides of Virgin Basin.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 4, PP. 387–404
FIGS. 1–4, DECEMBER, 1957

A STATISTICAL STUDY OF HEAVY MINERALS IN SANDS OF THE SOUTH RIVER, AUGUSTA COUNTY, VIRGINIA[1]

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ABSTRACT

A study of the variation in distribution of heavy minerals in stream bed sands of some tributaries of the South River, Augusta County, Virginia, was planned according to a nested sampling design so that the results of grain counts could be examined by the analysis of variance. The sampling design provided data for comparing heavy-mineral content on the two sides of the main stream, in five tributaries on each side, in four sampling localities in each tributary, and in three counts on each heavy-mineral slide. The study showed that both ilmenite and zircon differed significantly percentagewise between the tributaries within a side, and when the data were expressed as weight in grams, these also differed significantly between the sides.

The heavy minerals were derived from sedimentary rocks of Early Cambrian to Early Ordovician age, with one tributary obtaining minerals from Precambrian(?) rocks. The mineral assemblages have few species, as is common in sandstones and limestones. Opaques (largely ilmenite), zircon, tourmaline, rutile, and epidote are the most abundant minerals. The study was restricted to the grains in the 0.12- to 0.06-mm grade (−120 +230 mesh U. S. Standard Sieves).

INTRODUCTION

The investigation of heavy minerals in sands, soils, and other unconsolidated materials with the object of proving similarity or dissimilarity of the assemblages for purposes of correlation of source and origin often presents a problem in sampling and nearly always a problem in the interpretation of results. How sure can one be that the interpretation is justified from the number of samples and from the quantities of the different mineral grains present in the heavy residues? In the field, sampling has to be on a practical basis because of limiting factors such as time, cost, transportation, accessibility of sample sites, and, later, examination of samples in a laboratory. Although it is true that one sample from an outcrop, beach, soil type, or river sand, is better than none at all, many geologists, including the writer, have felt the need for guidance in this matter. The recent establishment of a Committee on Statistics in Geology in the Geologic Division of the U. S. Geological Survey has made such guidance available, and the study of heavy minerals in river sands reported in this paper was planned with the help of professional consultants to the Committee.

The objectives of the study were:

1.—To take a supposedly simple geological situation for heavy-mineral study and to collect from it samples that could be examined on a statistical basis as in a planned experiment.

2.—To plan the field sampling and laboratory examination so that the maximum use could be obtained from the material by statistical analysis.

3.—To use the analysis of variance to interpret the results.

4.—To interpret the statistical findings in the light of number of samples required to obtain information about differentiating the various mineral assemblages from various sources.

5 —To show how detailed examination in one part of an area or formation can be used as a basis for the interpretation of results from a larger area.

In this investigation the heavy minerals present in the stream-bed sands of tributaries entering a main stream from opposite sides and draining across different kinds of rocks were studied. The tributaries of the South River, Augusta County, Virginia, were selected for this purpose (fig. 1).

The more specific objectives were: differentiation of heavy-mineral assemblages of north- and south-side tributaries; evaluation of mineral variation within tributaries and between tributaries; evaluation of the variation in content of heavy residues in the samples; variability in grain counts in

[1] Publication authorized by the Director, U. S. Geological Survey. Manuscript received February 23, 1957.

samples; contribution of individual minerals towards differentiation of the assemblages.

PLAN OF STUDY

The following properties of the heavy residues of the stream-bed sands were used in this study:

1.—The quantity (weight) of heavy residue in the 0.12- to 0.06-mm grade of the sands.

2.—The frequency of occurrence of opaque grains (mostly ilmenite) and of zircon as given by the percent by number in the individual samples of heavy residues.

3.—The quantity of opaques and of zircon as a weight percent of the heavy residue. (The weight percent was obtained by using a conversion factor on the figures for percent by number.)

4.—The frequency of occurrence of several different types of zircon in the heavy residues (expressed as a number percent).

The sampling plan used was the multilevel, hierarchical, or nested sampling design (Cochran, 1953, p. 215; Olson and Potter, 1954, p. 27; Potter and Olson, 1954, p. 50–73; Krumbein and Slack, 1956, p. 753) introduced into geology by Olson and Potter (1954). This plan permits the estimation of the variance components. In addition, subsampling of the grain counts gives data for the evaluation of laboratory errors (Krumbein and Slack, 1956, p. 759).

The sampling design used permitted estimation of variability at four levels:

A.—2 sides of main stream (north side draining Cambrian and Ordovician rocks; south side draining Lower Cambrian and Precambrian? rocks)

B.—10 tributaries of the main stream (5 on the north side, and 5 on the south side; see fig. 1)

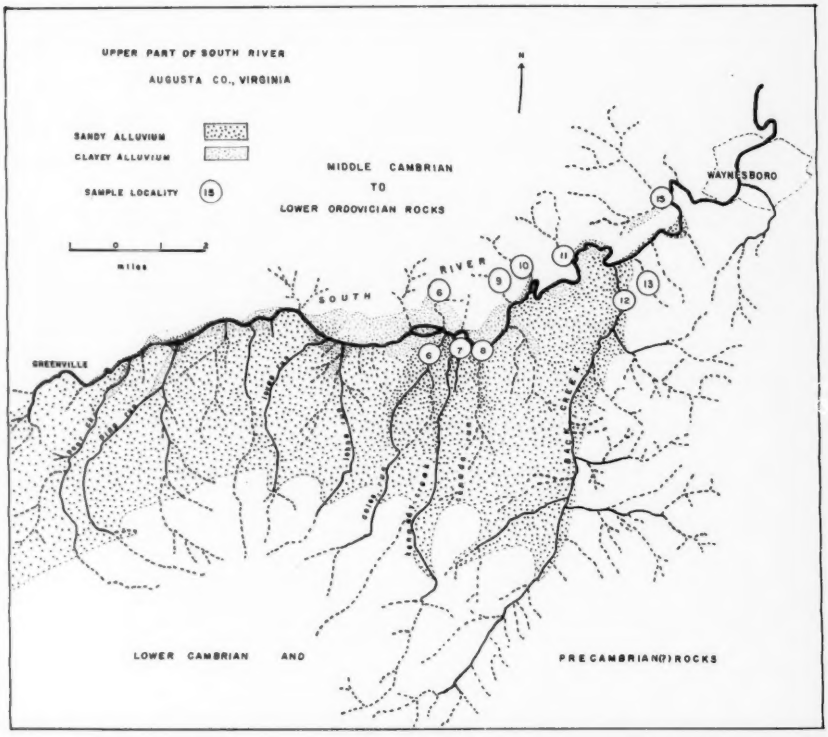

FIG. 1.—Map of upper part of the South River, Augusta County, Virginia, showing tributaries, sample localities, and generalized geology.

C.—4 samples (slides) for each tributary

D.—3 grain counts of 100 grains (quadrants) for each heavy mineral slide (see fig. 2)

Thus 40 stream-bed sands were collected and on these 120 observations were made on the heavy minerals, resulting in a count of 12,000 grains.

FIELD SETTING

The South River, south of Waynesboro, Augusta County, Virginia was selected for this study. Figure 1 shows the South River and its tributaries in relation to the geology of the area. Tributaries entering the main stream from the south side drain rocks on the northwestern flank of the Blue Ridge which consist of the Chilhowee Group (Antietam Sandstone, Harpers Shale, and Unicoi Formation of Early Cambrian age) and the Catoctin Formation (Precambrian?). Tributaries coming from the north are in Middle Cambrian to Lower Ordovician limestones (Conococheague, Elbrook, and Beekmantown Limestones). The assemblages of heavy minerals to be expected from the northern tributaries were known from previous work in the area by the author. It was to be expected that distinctive features such as varietal differences in mineral grains, if not different mineral species, would be carried by the southern tributaries draining members of the Chilhowee Group.

The tributaries of the South River thus provide a range of distinctive features in their heavy minerals which may be used to differentiate their sands and may be considered as examples of what could be found in many areas in most countries.

Figure 1 shows that there are five pairs of opposite tributaries of the South River (localities 6 to 15) and that the larger tributaries are on the southern side where they drain from the high ground in the foothills of the Blue Ridge. On the other hand the northern tributaries are shorter and rather intermittent but nevertheless provide samples of the heavy minerals characteristic of the Middle Cambrian and Ordovician rocks of the area. Two types of alluvium, a sandy alluvium from the southern drainage, and a clayey alluvium from the northern drainage cover certain areas near the South River but their influence on the mineralogy is not considered in this paper.

METHODS

Collection of Samples

Four samples were collected at randomized localities from the center of the bed of each tributary above its junction with the main stream. The distance above the mouth of the tributary was not measured, but the sampling locations are shown on figure 1. All the samples from one locality were within 200 yards of each other. The samples were collected in a small bucket and were placed wet in canvas bags. Each sample weighed about 2 lb; no separation of sand from pebbles or gravel was made in the field.

Laboratory Treatment

A flow sheet for the laboratory and subsequent treatment of the samples is given in figure 2, which outlines the processing of four samples from one locality (tributary). The pebbles and gravel were removed from the samples by wet sieving and the clay was washed out by agitation and decantation as in panning, leaving the sand fractions. The sand was dried and separated into Wentworth grades with U. S. Standard sieves. Where necessary, the bulk of the $-60+120$ (0.24–0.12 mm) and the $-120+230$ mesh (0.12–0.06 mm) grades were split to smaller sizes to give about 10 grams. Each fraction was then cleaned in 1:1 HCl, dried, weighed, and separated in bromoform to obtain the heavy residue. This was also weighed and recorded as a weight percent (fig. 3). Next, either the whole heavy residue, if small in size, or a portion of it obtained with a microsplitter was mounted in Canada balsam for microscopic examination and grain counts.

Although both the $-60+120$ and the $-120+230$ grades of sand were separated, inspection showed that the latter grade having grains 0.12 to 0.06 mm in diameter was the more suitable for this study. It is recognized that certain minerals tend to occur in larger or smaller grain sizes than others, but in this area all the minerals in these sands, with the possible exception of epidote from one tributary, have been subjected to previous sorting and sedimentation processes, so that any suggested bias by this procedure can probably safely be neglected from the mineralogical point of view.

Each heavy mineral mount of an even spread of grains under a circular cover slip

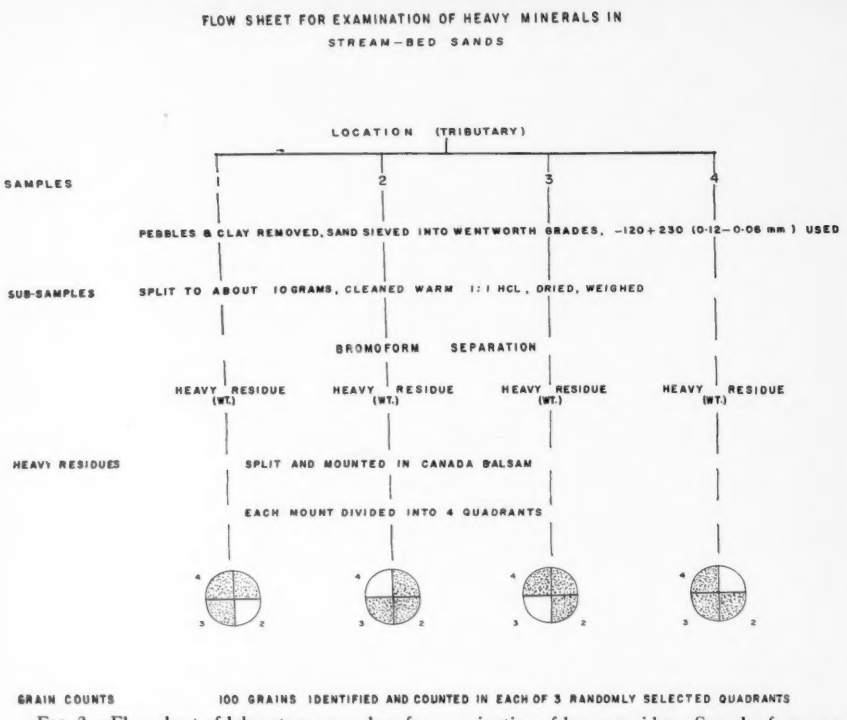

FIG. 2.—Flow sheet of laboratory procedure for examination of heavy residues. Samples from one tributary are shown. The same procedure was followed for each of the ten tributaries studied in this investigation.

was divided into four quadrants as shown in figure 2, and the mineral grains in three of these quadrants were counted using a mechanical stage and an automatic tabular computer. The quadrants in which the grains were counted were selected randomly by casting dice. Exactly 100 grains were counted in each quadrant. The microscope slide was placed in a mechanical stage and set in such a position that a large number of grains would be shown. The grains lying immediately beneath the horizontal cross hair were counted, and then the slide was moved by the vertical adjustment screw of the stage to another position to give another traverse of the grains. Thus 300 grains, 100 from each of three quadrants, were counted and the results were tabulated as in table 1, the average or mean then being calculated for each sample. The same procedure was followed for each sample (slide).

MINERALOGY

The minerals in the heavy residues are: ilmenite with a little hematite or goethite or both, labelled as opaques, zircon, and tourmaline, which together generally constitute over 90 percent of the heavy minerals. Small quantities of rutile, epidote, amphibole, chloritoid, staurolite, garnet, anatase, brookite, sillimanite, corundum, and sphene are the remaining minerals in these residues. Among the latter minerals only epidote is present in sufficient quantity to be of importance, although qualitatively they are all of interest in characterizing the mineral assemblages. The variation in percentage of these minerals is shown in figure 4 where each tributary is shown to have four samples, each sample being an average or mean count obtained from individual counts as shown in figure 2. Figure 4 also gives the

average composition for the total north side and the total south side tributaries.

The same minerals are common to all the samples with only minor variations in the least common species. Tables 2 and 3 give the percentage composition of the heavy residues in the sands from the north side and the south side tributaries, respectively. It is apparent from tables 2 and 3 and from figure 4, that there is considerably more variation in mineral composition in the south side tributaries than in the north side tributaries. This can be accounted for by the varying source rocks of the south side tributaries and also by the greater gradient of these streams (fig. 1). This is reflected in the variation in quantity of heavy minerals, expressed as a weight percent of the sand in figure 3.

Another feature of the heavy minerals is

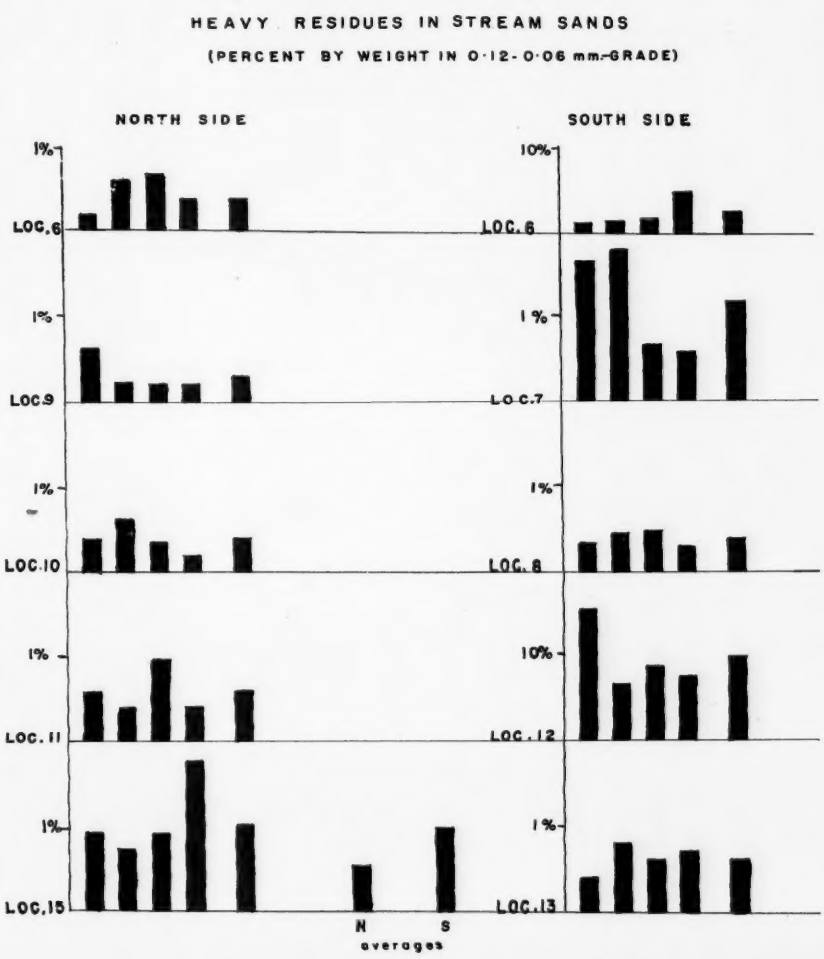

FIG. 3.—The percent by weight of heavy residue in the −120 +230 (0.12–0.06 mm) grade sands from each of the samples. The fifth column for each location (tributary) is the mean or average percent.

TABLE 1.—*Grain counts for three quadrants in one heavy residue of a sample of sand (−120+230 grade) from location 6, South River, Augusta County, Virginia*

Sample No.	Minerals								
	Opaques (ilmenite)	Zircon	Tourmaline	Rutile	Epidote	Staurolite	Chloritoid	Unidentified	Number of grains
Sample No. C-11									
Quadrant 2	30	41	23	1	1	1	2	1	100
Quadrant 3	35	43	15	6	—	—	1	—	100
Quadrant 4	46	32	20	1	1	—	—	—	100
Total	111	116	58	8	2	1	3	1	300
Average (per cent)	37	38	19	2.6	0.6	0.3	0.9	0.3	100

that both zircon and tourmaline occur in several varieties which can be used to differentiate a number of the samples. The varieties of zircon identified are given in table 4. These can be treated as individual minerals in statistical analysis. Tourmaline is not a major mineral, and although characteristic of these sands, is not present in sufficient quantity in all the samples for the type of statistical analysis used.

The random selection of parts of the heavy residue to be counted was done to minimize the counting error and to obtain an effective spread of observations from each heavy residue. The selection also contributes to the variance analysis by defining the laboratory error of counting.

The percent by number of the opaque grains and of zircon can be converted to percent by weight in the whole heavy residue by using a factor obtained from the average weight of a number of individual grains in the grade size of sand examined. Conversion factors were made for the −120+230 (0.12–0.06 mm) grade of zircon and ilmenite by taking a weighed quantity of a purified sample of each of these minerals and counting the number of grains in this weight under a microscope.[2] The counting was facilitated by using a slide divided into square grids with sides about 2 mm in length. As the specific gravity of zircon is 4.5–4.7 and of ilmenite is 4.5–5.0, a single conversion factor can be used for both minerals. This was found to be 100 grains equals 0.65 mg.

The conversion to weight percent was made because the weight of any mineral present in a heavy residue (or in the sand as a whole) is an important property of that sand; common examples such as the enrichment of a sand in minerals like zircon, ilmenite, monazite, or rutile in quantities of commercial importance illustrate this point. Inasmuch as the amount of heavy residue varies in the sands described here, the weight of the two principal minerals, ilmenite and zircon, is an additional property that can be used as a variance component.

STATISTICAL ANALYSIS OF DATA

The nested sampling design outlined under Plan of Study was arranged so that by the analysis of variance, the methods which have been fully described by Olson and Potter (1954) and by Krumbein and Slack (1956), the variation from each source could be assessed as part of the total variation. Thus variation in quantity of heavy residue being added to the main stream from the south side tributaries and from the north side tributaries is related to the individual tributaries and to the samples collected from the tributaries. The mineral grains within the samples from the tributaries show a similar variation.

Analysis of variance can be used for counts of heavy minerals, expressed as a number percent, because the population will have an approximately normal distribution (Dixon and Massey, 1951, p. 47–49).

[2] These conversion factors were computed prior to the publication of a paper by Kellagher and Flanagan (1956) on the same subject.

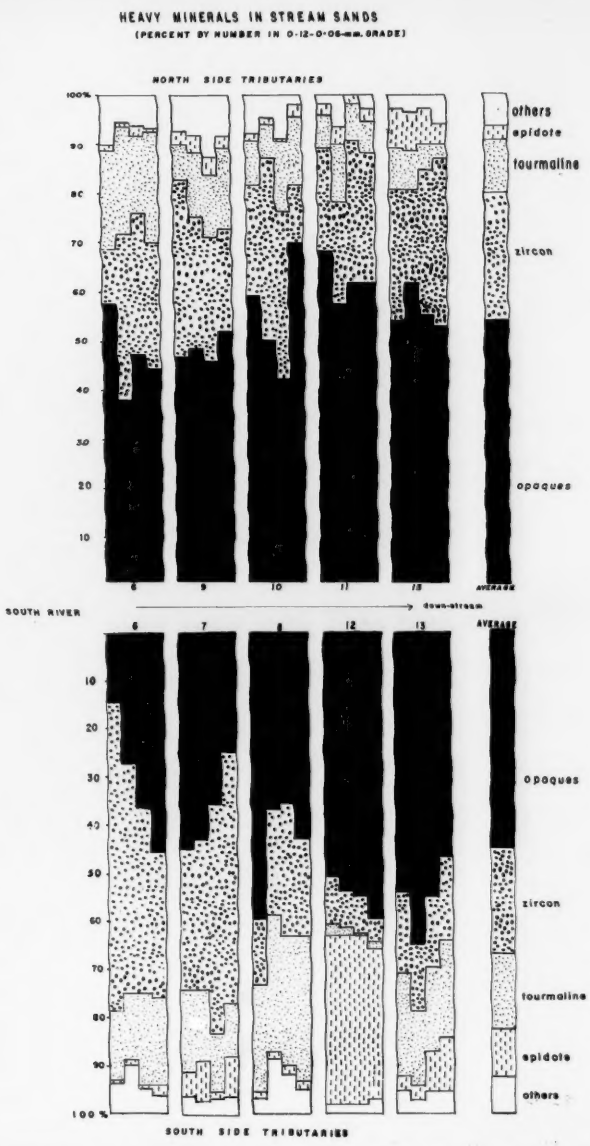

FIG. 4.—Minerals present in the heavy residues of the −120 +230 (0.12–0.06 mm) grade sands of tributaries of the South River. Each tributary is placed diagrammatically in the position in which it occurs with respect to the main stream whose direction of flow is from west to east. North side tributaries drain Middle Cambrian to Lower Ordovician rocks; south side tributaries drain Lower Cambrian and Precambrian (?) rocks.

TABLE 2.—*Heavy minerals, (percent by number) in stream-bed sands (−120+230 grade) from north side tributaries of the South River, Augusta County, Virginia (localities given in fig. 1)*

North Side Tributaries

Sample No.	Minerals												
	Opaques	Zircon	Tourmaline	Rutile	Epidote	Chloritoid	Amphibole	Staurolite	Garnet	Sphene	Sillimanite	Corundum?	Unidentified
Locality 6													
C 17	57.0	11.6	22.0	3.3	1.3	.6	—	.3	.3	—	—	—	—
C 18	37.6	34.6	21.6	3.6	.6	1.0	—	—	—	—	—	—	—
C 19	46.6	29.0	16.3	2.0	2.0	—	—	.3	—	.3	—	—	—
C 20	43.3	27.0	23.3	4.3	.6	.6	—	—	—	—	—	—	—
Mean	46.1	25.5	20.8	3.3	1.1	—	—	—	—	—	—	—	—
Locality 9													
C 25	46.3	37.6	7.3	3.3	3.3	—	—	—	.6	—	—	.3	.6
C 26	48.6	27.6	13.6	3.0	4.0	.3	.6	—	1.0	—	—	—	.6
C 27	45.6	26.0	13.3	8.3	3.3	1.6	—	.3	.6	—	.3	—	.3
C 28	52.6	21.0	16.6	5.6	3.0	1.0	—	.3	1.0	.6	.6	—	—
Mean	48.2	38.0	12.7	5.0	3.4	—	—	—	—	—	—	—	—
Locality 10													
C 29	59.3	23.0	9.0	5.6	1.6	.6	—	—	—	—	—	.6	—
C 30	50.3	37.6	7.6	2.0	1.0	.3	—	.3	—	—	—	—	—
C 31	42.6	34.6	15.6	2.6	.3	.6	—	—	—	—	—	—	.6
C 32	70.6	12.0	13.6	.6	2.0	—	1.0	—	—	—	—	—	—
Mean	55.7	26.8	11.4	2.7	1.2	—	—	—	—	—	—	—	—
Locality 11													
C 33	68.6	21.3	7.3	.3	2.0	—	—	—	—	—	—	.3	—
C 34	57.0	21.6	12.6	2.3	4.0	1.0	—	—	—	—	—	—	.6
C 35	62.0	29.6	7.0	1.0	3.0	—	.3	—	—	—	—	—	.3
C 36	62.6	26.3	7.3	.6	2.6	—	.3	—	—	—	—	—	—
Mean	62.5	24.7	8.5	1.0	2.9	—	—	—	—	—	—	—	—
Locality 15													
C 45	54.0	27.0	8.0	1.0	8.3	—	—	—	1.0	—	—	—	.3
C 46	62.6	19.3	7.6	1.6	8.0	—	.6	—	—	—	—	—	—
C 47	55.3	30.6	5.3	.6	7.0	—	—	—	.3	—	.6	—	—
C 48	53.6	34.0	3.3	1.0	7.6	—	—	—	.3	—	—	—	—
Mean	56.4	27.7	6.0	1.0	7.7	—	—	—	—	—	—	—	—

It is necessary, however, that the individual minerals used in the analysis form a large percentage of the total and occur in each sample examined. For this reason analyses of variance were confined to the two most abundant minerals in these residues, opaques and zircon.

The data in tables 2, 3, 4, and 5 were analyzed in two variance patterns:

I.—As a nested sampling design of four levels—groups (1), (2), and (4) given under Plan of Study and concerned with the weight of heavy residues, the frequency of occurrence of opaques and zircon, and the occurrence of types of zircon. The analyses are set out in tables 6, 7, 8, and 9.

II.—As a comparison of variances of the mean weight of opaques and of zircon for the two sides of the main stream, based on mean values for the four samples in each tributary. This is given in tables 11 and 13.

The separation of the variability at each sampling site is:

A.—Between sides of main stream

B.—Between tributaries on a side

C.—Between samples (slides) within a tributary

D.—Between quadrants (counts) within a slide.

The significance of the variability at each sampling site for each attribute of the heavy

residues which was examined in this study by testing (i) the mean square for "Between sides of main stream" against (ii) the mean square for "Between tributaries on a side," and (ii) against (iii) "Between samples within a tributary." This procedure is correct if there are many tributaries on each side of a main stream and there are many possible samples at a site. In this study a selection of the tributaries available for sampling was made according to geographic situation and accessibility with the object of obtaining an equal number draining across the two principal geologic source areas. The assumption is implied that the two sides of the same main stream have the same mean mineralogical content, which in fact (from fig. 2) is almost correct. Statistically, however, there is no simple test of the hypothesis that the two sides of the main stream have the same mean.

The variation in the mean squares of the data in the various tables are tested for significance by the F test or variance ratio (Snedecor, 1946, p. 219). To do this, inferences are made from the mean squares (σ^2). At each level, i.e., (i), (ii), and (iii) described in the preceding paragraph, an F test is made to identify the probability of $\sigma_1^2 = \sigma_2^2$, and $\sigma_2^2 = \sigma_3^2$. Hypotheses are postulated for the F tests as shown for the various sets of data.

TABLE 3.—*Heavy minerals, (percent by number) in stream-bed sands (−120+230 grade) from south sid tributaries of the South River, Augusta County, Virginia (localities given in fig. 1)*

South Side Tributaries

Sample No.	Minerals											
	Opaques	Zircon	Tourmaline	Rutile	Epidote	Chloritoid	Amphibole	Staurolite	Garnet	Sphene	Sillimanite	Unidentified
Locality 6												
C 9	46.3	30.6	18.6	1.6	2.0	—	.3	—	—	—	—	—
C 10	37.0	38.6	19.3	2.6	.3	1.0	—	.3	—	—	—	.3
C 11	28.3	47.6	14.3	3.6	1.0	.6	—	.6	—	—	—	.3
C 12	15.3	64.3	14.0	2.6	.3	—	—	—	—	—	—	—
Mean	31.7	45.2	16.5	2.6	.9	—	—	—	—	—	—	—
Locality 7												
C 13	25.0	52.0	11.6	1.3	8.3	1.0	—	.3	—	—	—	.3
C 14	36.6	47.0	12.0	1.3	1.3	1.3	—	—	—	—	—	.3
C 15	43.0	31.6	15.3	2.0	8.3	1.3	—	1.6	—	—	—	.3
C 16	45.0	29.0	17.3	1.3	5.3	.6	—	.6	—	—	—	.3
Mean	37.4	39.9	14.0	1.5	5.8	1.0	—	—	—	—	—	—
Locality 8												
C 21	43.3	20.0	30.6	2.0	1.3	2.0	.3	—	—	—	—	.6
C 22	36.6	27.0	27.6	3.3	1.6	2.3	—	.3	—	—	.3	.3
C 23	37.3	22.6	28.3	6.3	1.6	3.6	—	—	—	—	—	—
C 24	60.3	13.0	22.3	1.3	1.3	1.3	—	—	—	—	—	.3
Mean	64.3	20.6	27.2	3.2	1.4	2.3	—	—	—	—	—	—
Locality 12												
C 37	59.6	4.3	1.3	2.6	31.3	.3	—	—	—	.3	—	—
C 38	55.3	7.6	.6	1.0	35.3	—	—	—	—	—	—	—
C 39	54.0	7.6	1.6	1.3	35.3	—	—	—	—	—	—	—
C 40	51.0	9.6	2.3	1.6	35.3	—	—	—	—	—	—	—
Mean	55.0	7.2	1.4	1.6	34.3	—	—	—	—	—	—	—
Locality 13												
C 41	47.3	17.3	20.3	1.6	11.0	1.6	—	—	.3	—	—	—
C 42	55.6	15.6	17.3	2.6	8.0	.3	.3	—	—	—	—	—
C 43	65.0	14.0	15.6	1.3	3.6	—	.3	—	—	—	—	—
C 44	54.6	17.6	21.3	2.0	2.3	.6	—	—	—	.6	—	.3
Mean	55.6	16.1	18.6	1.9	6.2	—	—	—	—	—	—	—

I. (1) *Quantity of heavy residue in the 0.12- to 0.06-mm grade*

The weight of heavy residue in the samples from all tributaries is given in table 5. The weight percent figures for the north side tributaries (B) are reasonably homogenous, but those for the south side tributaries (A) are not, those most noticeably inhomogenous being the large heavy mineral contribution made by tributary 12. An analysis of variance using these figures is given in table 6, but because of the inhomogeneity of the data, they should perhaps have been transformed (Snedecor, 1946, p. 445) before tests of significance of variance (F tests) were performed.

The significance of the variability of the data in table 6 can be examined by postulating two hypotheses, H (i) and H (ii) on which F tests are performed. The hypotheses are:

H (i) There is no greater variability in the weight percent of heavy residue between the stream sides than between the tributaries on a side.

H (ii)—There is no greater variability in the weight percent of heavy residue between tributaries on a side than between the samples from a tributary.

The F values are:

H (i) $A/B = 179/27/7 = 6.46^{*}$; $F_{.95}(1, 8) = 5.32$

H (ii) $B/C = 27.7/4.2 = 6.59^{**}$; $F_{.99}(8, 30) = 3.17$

As the F values for both (i) and (ii) are greater than the 5 percent critical values of the F distribution (Dixon and Massey, 1951, table 7), the hypotheses are rejected. The geological implications of these tests are: (i) the weight of heavy residue being added from each side is significantly different; and (ii) the weight of the heavy residues is a significant property of the tributaries and can be used to differentiate one from another. (fig. 3.)

The variance of 4.2 for the samples indicates that there is not much variation within each tributary, which is important from the point of view of the number of samples required.

TABLE 4.—*Types of zircon in samples of sands from north and from south side tributaries of the South River, Augusta County, Virginia (localities given in fig. 1)*

Types	1%*	2%	3%	4%	5%	6%
North side tributaries—draining Middle Cambrian to Lower Ordovician rocks						
Locality 6	13	1.5	1.7	13.5	40	30
Locality 9	31	.5	1	15	33	19
Locality 10	35	1	1.5	16	30	16
Locality 11	34	2.5	1	18	29	14
Locality 15	29	4.7	2	17	28	17
Average:	29	2	1.5	16	32	19
South side tributaries—draining Lower Cambrian and Precambrian (?) rocks						
Locality 6	11	3.7	2.2	6	46	28
Locality 7	24	2.7	2.7	8	35	28
Locality 8	9	2.7	2.7	9	43	32
Locality 12	7	27	3	17	30	14
Locality 13	17	15	2	5	41	18
Average:	14	15	2.6	9	39	24

* Percent by number in zircon population obtained from a count of 100 randomly selected grains.

Description of Types of Zircon

1. Well-rounded, colorless, polished or matt surface; the most highly polished grains are characteristic of the Conococheague limestone.
2. Purple, well-rounded (very few grains show crystal faces).
3. Metamict, rounded or angular.
4. Angular, colorless, showing no abrasion effects.
5. Colorless grains showing moderate wear and distinct from (1); generally no crystal faces are recognizable.
6. Angular, but with some rounding of the crystal faces which, however, are still recognizable.

I. (2a) *Frequency of occurrence of opaque grains (number present) in the 0.12- to 0.06-mm grade*

The percent of opaque grains for each sample from tributaries on the north side is listed in table 2 and for the tributaries on the south side in table 3. These figures are used for an analysis of variance.

This analysis of variance gives the following hypotheses and the geologic significance which can be obtained from them:

H (i) There is no greater variability in opaque grains (percent by number) in the residues between stream sides than between tributaries on a side.

$F_{.95}(1, 8) = 2.58$ NS

TABLE 5.—*Weight percent of heavy minerals in the −120+230 (0.12–0.06-mm) grade sand from bed of south side and of north side tributaries, South River, Augusta County, Virginia*

A. South Side Tributaries

Tributaries	6	7	8	12	13	Total
Samples 1	.96	1.64	.35	15.7	.38	
2	1.70	1.76	.46	6.9	.78	
3	1.50	.70	.49	9.2	.64	
4	4.86	.63	.29	8.0	.68	
EX	8.52	4.73	1.59	39.8	2.48	57.12
Mean	2.13	1.18	.40	9.95	.62	2.85

B. North Side Tributaries

Tributaries	6	9	10	11	15	Total
Samples 1	.18	.67	.39	.63	.96	
2	.58	.23	.62	.38	.73	
3	.61	.22	.36	.94	.92	
4	.38	.23	.18	.43	1.76	
EX	1.75	1.35	1.55	2.38	4.37	11.4
Mean	.44	.34	.40	.59	1.1	.57

H (ii) There is no greater variability in opaque grains (percent by number) between the tributaries than between the samples from a tributary.

$$F_{.95}(8, 30) = 4.0^{*}$$

H (iii) There is no greater variability in opaque grains (percent by number) between samples (slides) than between quadrants (counts) within a slide.

$$F_{.99}(30, 80) = 5.7^{**}$$

The variance ratio, F, shows that there is no significant difference in the percent by number of opaque grains in the residues on either side of the main stream. This is shown by the letters NS after the F value given above. The individual samples obtained within a tributary do not vary as much as the mean of each group of four samples from the various tributaries. This is given by hypothesis (ii), the F ratio of which is significant at the 5-percent level. Each sample, therefore, is truly representative of the distribution of the opaque grains at the locality sampled, that is, of the particular tributary. And, finally, hypothesis (iii) shows that there is a significant difference at the 1-percent level between the variation in the samples and that in the counts. This means that any effect of counting does not obscure the differences between the samples, which is an important fact because differentiation of samples or groups of samples by heavy mineral counts is one of the major objectives of this and many other investigations.

I. (2b) *Frequency of occurrence of zircon (number percent in the 0.12- to 0.06-mm grade sands*

The percent of zircon in each sample from tributaries on the north side is listed in table 2 and for the tributaries on the south side in table 3. These figures are used for an analysis of variance.

The same set of hypotheses as those used for the opaque grains (table 7) are applicable to the zircon distribution in the heavy

TABLE 6.—*Analysis of variance of heavy residue in the 0.12- to 0.06-mm grade*

Source	Degrees of freedom	Sum of squares	Mean square, σ^2
(A) Between sides of main stream	1	179	179
(B) Between tributaries on a side	8	222	27.7
(C) Between samples within a tributary	30	126	4.2

TABLE 7.—*Analysis of variance of content of opaque grains (percent by number) in the 0.12- to 0.06-mm grade sands*

Source	Degrees of freedom	Sum of squares	Mean square, σ^2
(A) Between sides of main stream	1	2548	2548
(B) Between tributaries on a side	8	7133	891
(C) Between samples (slides) within a tributary	30	6648	222
(D) Between quadrants (counts) within a slide	80	3144	39

residues. The results are (using the same numbers for the hypotheses):

H (i) $F_{.95}(1, 8) = 0.01$ NS

H (ii) $F_{.95}(8, 30) = 2.5^*$

H (iii) $F_{.99}(30, 80) = 6.0^{**}$

Zircon distribution follows a pattern similar to that of the opaque grains. There is even less variability between the two sides of the main stream for zircon than there is for opaque grains. Geologically, however, the analysis of variance for zircon distribution tends to obscure the actual circumstances because there is a very great variation in zircon content of the individual south-side tributaries (fig. 4) although the mean zircon content for the north side is not very different from the mean for the south side.

For hypothesis (iii) there is a highly significant difference, at the 1-percent level, between the variation in the samples as against that in the counts. It is noteworthy that the F values for this hypothesis are practically identical for the opaque grains and for zircon grains. The analysis of variance for the zircon distribution serves to strengthen the findings for the opaque grains and, therefore, of the investigation as a whole.

I. (4) *Variation in frequency of occurrence of different types of zircon in the 0.12- to 0.06-mm grade sands*

The zircon population of the heavy residues was divided into six easily recognized types and the number of each type found in 100 randomly selected grains was tabulated (table 4). Inspection shows that there are certain rather striking differences particularly with regard to the quantity of well-rounded zircons and purple zircons, the latter being of somewhat sporadic occurrence. Are these differences sufficient to differentiate the north-side tributaries from the south-side tributaries?

Examination of table 4 shows that only zircon types 1, 5 and 6 are present in sufficient quantity to justify an analysis of variance. The figures are observations made on 40 samples (4 samples from each of 10 locations (tributaries)) and include 4000 zircon grains. The individual counts for each locality have been arranged so that the figures given in table 4 are the means of the zircon population.

Analyses of variance of type 1 (well rounded with polished or matt surface), type 5 (grains showing moderate wear, with no crystal faces) and type 6 (angular grains with only slight wear on the crystal faces) are given in table 9.

Table 9 shows how varietal types of zircon may be used as a refinement of the figures for percent (by number) of zircon grains in the residues to differentiate possible sources of material. Varietal features of zircon are very often used to distinguish mineral suites derived from different parent rocks.

The hypotheses arising out of the analysis of variance in table 9 are:

TABLE 8.—*Analysis of variance of content of zircon (percent by number) in the 0.12- to 0.06-mm grade sands*

Source	Degrees of freedom	Sum of squares	Mean square, σ^2
(A) Between sides of main stream	1	17	17
(B) Between tributaries on a side	8	4434	554
(C) Between samples (slides) within a tributary	30	6459	216
(D) Between quadrants (counts) within a side	80	2748	35

TABLE 9.—*Analyses of variance of zircon types 1, 5, and 6 in the 0.12- to 0.06-mm grade sands*

Source	Degrees of freedom	Zircon (1)		Zircon (5)		Zircon (6)	
		Sum of squares	Mean square σ^2	Sum of squares	Mean square σ^2	Sum of squares	Mean square σ^2
(A) Between sides of main stream	1	1782	1782	483	483	265	265
(B) Between tributaries on a side	8	2310	288	2518	314	2233	280
(C) Between samples within a tributary	30	653	21	823	27	246	8.2

H (i)—There is no greater variability for zircon (percent by number) of Type 1 (5, or 6) between the stream sides (implying sources or origin) than between tributaries on a side.

H (ii)—There is no greater variability for zircon (percent by number) of Type 1 (5, or 6) between the tributaries than between the samples within the tributaries.

The significance of the F ratio in each of these hypotheses will now be given for each type of zircon:

Zircon, Type 1 (well-rounded; polished or matt surfaces)

H (i) $F_{.95}(1, 8) = 6.18^{**}$

H (ii) $F_{.99}(8, 30) = 13.7^{**}$

These F ratios show that there is a difference in distribution between the two sides of the main stream, and a highly significant difference, at the 1-percent level, between the content of this type of zircon in the different tributaries.

The conclusion is that the distribution of Type 1 zircon is worth examining further as an indicator of provenance

Zircon, Type 5 (grains with moderate wear)

H (i) $F_{.95}(1, 8) = 1.5$ NS

H (ii) $F_{.99}(8, 30) = 11.6^{**}$

There is no significant difference in distribution between the two sides of the main stream for Type 5 zircon, but there is a highly significant difference, at the 1-percent level, between the individual tributaries. Such zircon is of little diagnostic value or interest in the heavy mineral assemblages as a whole, although tributary variations may point to local sources.

Zircon, Type 6 (angular grains with very slight wear on crystal faces)

H (i) $F_{.95}(1, 8) = 0.94$ NS

H (ii) $F_{.99}(8, 30) = 34^{**}$

The same remarks apply to Type 6 zircon as were made for Type 5 zircon. Apparently there are localized sources of angular zircon contributing to some of the tributaries. This strongly suggests that one or more beds of rock crossed by one or more tributaries are the source of this zircon and that further investigation of the distribution of Type 6 zircon is required.

Although there are no significant differences in the percent by number of opaque grains or of zircon in the sands from either side of the main stream (tables 7 and 8), there is a difference in the actual weight of heavy residue found in the sands (table 6). This suggests that where the total residue weighs more there will actually be more

TABLE 10.—*Weight in grams of opaque grains in the heavy residue of the 0.12- to 0.06-mm grade sands in tributaries of the South River, Augusta County, Virginia*

	Weight* percent of opaque grains				
North side tributaries**	6	9	10	11	15
	0.20	0.16	0.22	0.38	0.62
South side tributaries**	6	7	8	12	13
	0.68	0.45	0.18	5.58	0.33

* Mean of four samples collected from each tributary.

** Locations are given on figure 1.

TABLE 11.—*Variances for weight percent of opaque grains in the 0.12- to 0.06-mm sands in tributaries of the South River, Augusta County, Virginia*

	Degrees of freedom	Sum of squares	Mean square, σ^2
Variance for north side tributaries	4	0.1437	0.036
Variance for south side tributaries	4	21.51	5.37

opaque grains and zircon in the sands as a whole. The distribution of these two groups of minerals can be weighted for source, i..e, for tributary contribution, implying a distribution from a source. In order to compare the two sides of the main stream by means of the tributary contributions the weight percent figures for each sample within a tributary were averaged and the variance obtained for the north side and for the south side of the main stream. The variances were then compared using appropriate F tests.

II. (3a) *Quantity of opaque grains as a weight percent of the total heavy residue in the 0.12- to 0.06-mm grade sands.*

The figures for percent by number for the opaque grains were converted to percent by weight using a conversion factor of 100 grains equals 0.65 mg to give the figures in table 10.

From the figures in table 10 the variance in mean percent by weight of the opaque grains for the north-side sands and for the south-side sands were computed as given in table 11.

The significance of the variability between north-side tributaries and the south-side tributaries, as given in table 11, is examined by postulating that there is no greater variability in the weight of opaque grains carried by the south-side tributaries than between the tributaries on the north side. An F test gives the relationship:

$$\text{F south side vs. north side} = \frac{5.37}{0.036} = 150^{***},$$

$$F_{.995}(1, 8) = 14.7,$$

indicating a highly significant difference at the 0.5-percent point.

Inspection of table 10 shows, however, that most of this difference is caused by one tributary, Back Creek (fig. 1, locality 12), a large well-established stream draining Precambrian(?) rocks that are apparently a better source of heavy minerals than the sedimentary rocks of the Chilhowee Group.

Recalculation of variance between the north-side tributaries and south-side tributaries omitting the large contribution of tributary 12 from the south side gives $F = 0.61$ NS with $F_{.95}(1, 7) = 5.59$, showing that there is no significant difference in the weight of opaque grains contributed by the tributaries on either side of the main stream. Geologically this is interesting in showing the influence of uneven contributions from streams draining different source rocks on the validity of statistical analysis in such a situation, which is probably a very common one for streams and their tributaries.

II. (3b) *Quantity of zircon grains as a weight percent of the total heavy residue in the 0.12- to 0.06-mm grade sands.*

The figures for percent by number for zircon were converted to percent by weight using a conversion factor of 100 grains = 0.65 mg to give the figures in table 12.

From the figures in table 12 the variance in mean percent by weight of the zircon grains for the north side sands and for the south side sands were computed as given in table 13.

The hypothesis that the variance of the zircon in the north-side tributaries is similar to that of the south-side tributaries is tested in a similar manner to that for the opaque grains in (3a) above, south vs. north,

$$F = \frac{0.1487}{0.0075} = 19.8^{**}, \qquad F_{.995}(1, 8) = 14.7$$

Table 12 indicates that there is a considerable variation in the weight of zircon carried by the main stream, the mean weight for the north-side tributaries is 0.16 percent, and for the south-side tributaries, 0.46 percent. There is, however, no conspicuously large amount such as occurs for opaque grains in tributary 12, south side. Therefore the validity of the F test for zircon is not open to query.

This analysis of the data shows that, as in the case of the opaque grains, the populations of zircon considered geologically are

TABLE 12.—*Weight in grams of zircon grains in the heavy residue of the 0.12- to 0.06-mm grade sands in tributaries of the South River, Augusta County, Virginia*

	Weight* percent of zircon grains				
North-side tributaries**	6	9	10	11	15
	0.16	0.09	0.10	0.15	0.31
South-side tributaries**	6	7	8	12	13
	0.96	0.49	0.08	0.71	0.09

* Mean of four samples collected from each tributary.
** Locations are given on figure 1.

distinct, implying differences in sources or in stream activity or in both.

DISCUSSION

The results of the analyses of variance of the data from weight of heavy residues, grain counts of opaque grains and zircon, grain counts of varietal types of zircon, and weight of opaque grains and of zircon in this nested sampling design clearly show that this method is applicable to heavy-mineral investigations and that it yields interesting and important information.

If the variance analyses had been confined to the percent by number of opaque grains and of zircon in these heavy residues the extra laboratory work in processing and counting four samples instead of one from each tributary probably would not have been justified because the relationships can be interpreted from figure 4 where the mean value or average for each side of the main stream is seen to be similar. But other facts can also be used for interpreting the relationships, and these are emphasized by the analyses of variance. The facts and their interpretation can be set out briefly as follows:

1.—Quantity of heavy residue	Different on either side of main stream
2.—Opaque grains, percent by number in the residues	Not significantly different on either side, but significantly different in the tributaries
3.—Zircon, percent by number in the residues	Not significantly different on either side, but significantly different in the tributaries
4.—Varietal types of zircon, percent by number in zircon population	One type is significantly different on either side of main stream; this indicates use in provenance studies
5.—Weight of opaque grains in grade of sand studied	Significantly different on either side of main stream
6.—Weight of zircon in grade of sand studied	Significantly different on either side of main stream
7.—Relationship between grain counts and tributary variability	In each case examined the variability in tributaries is greater than in grain counts in quadrants in the slides (samples)

The analyses of variance have shown that errors in grain counts are insignificant in relation to the real differences in samples from the various tributaries. As this is so, will it be necessary or desirable to use more than one sample, that is, a count of 300 grains in one heavy residue (as shown in fig. 2) for each tributary to distinguish it from other tributaries and to obtain similarities and differences between the two sides of the main stream? This point can be examined by taking the results for the first sample collected from each tributary and using only the percent by number for the five most abundant heavy minerals and the weight of the heavy residue. These figures are set out in table 14.

The means for the north-side tributaries and the south-side tributaries using only one sample (the one that would normally be col-

TABLE 13.—*Variances for weight percent of zircon in the 0.12- to 0.06-mm sands in tributaries of the South River, Augusta County, Virginia*

	Degrees of freedom	Sum of squares	Mean square, σ^2
Samples from north-side tributaries	4	0.0311	0.0075
Samples from south-side tributaries	4	0.5947	0.1487

lected in a study of this kind) can now be compared with the means obtained by using all four samples from each tributary. These two sets of figures are given in table 15.

The means for the north-side tributaries and the south-side tributaries using only one sample can now be compared with the means using four samples from each locality.

Table 15 shows that by using only one sample from each tributary the percentage grain count, using 300 grains, is not greatly different from the mean obtained by using four samples from each tributary. This would seem to indicate that for this area and this type of material the time and cost of laboratory processing and mineralogical examination of four samples from each tributary is not justified. Any weakness that may lie in the accuracy of grain counts obtained by one operator to express a population estimate can probably be discounted as the grain counts will be mutually comparable. The figure of 300 is due to Dryden (1931) who investigated grain-count accuracy and pointed out that the accuracy increases as the square root of the number counted and that 4549 grains should be counted for an accuracy of 1 percent.

However, from the results of this investigation it seems that a count of 300 grains (random count of 100 in each of three quadrants on a slide) from one sample at a locality is well within the mean standard deviation obtained for the samples from each set of five tributaries. However, in other investigations if the samples are collected from farther apart, or if it is suspected that geological conditions have changed rapidly in the area being sampled, then additional samples should be collected and analyzed. In this part of the South River Basin and for this type of investigation, mixing of four samples from each tributary in the field would be a satisfactory procedure if one felt doubtful that one sample alone would not be representative.

CONCLUSIONS

This investigation was planned to show the application of statistics to a common problem in heavy-mineral examination and interpretation. It indicates the use that can be made of statistical evaluation of the results, and it gives confidence in inferences and deductions from the facts observed. Further, it enables one to find out whether detailed work is justified from the accuracy of the results obtained.

The stream sands of the tributaries of the South River are carrying almost exclusively heavy minerals derived from sedimentary rocks so that at first sight it would not seem possible that without major differences in mineralogy any differentiation could be made. However, by using the weight in grams of the opaque grains and zircon, to-

TABLE 14.—*Mineralogical composition of the heavy residues of the −120+230 (0.12–0.06 mm) grade sand of the first sample collected in each of the tributaries of the South River, Augusta County, Virginia*

Localities	6 %	9 %	10 %	11 %	15 %	Mean %
North Side Tributaries						
Opaques	57.0	46.3	59.3	68.6	54.0	57.0
Zircon	11.6	37.6	23.0	21.3	27.0	24.1
Tourmaline	22	7.3	9.0	7.3	8.0	10.1
Rutile	3.3	3.3	5.6	.3	1.0	2.7
Epidote	—	3.3	1.6	2.0	8.3	3.0
Weight heavy residue (g)	0.18	0.67	0.39	0.63	0.96	0.56
South Side Tributaries						
Opaques	46.3	25.0	43.3	59.6	47.3	44.2
Zircon	30.6	52.0	20.0	4.3	17.3	24.8
Tourmaline	18.6	11.6	30.6	1.3	20.3	16.5
Rutile	1.6	1.3	2.0	2.6	1.6	1.8
Epidote	2.0	8.3	1.3	31.3	11.0	10.8
Weight heavy residue (g)	0.96	1.64	0.35	15.7	0.38	3.80

TABLE 15.—*Comparison of means of mineralogical composition of the heavy residues in the −120+230 (0.12–0.06 mm) grade sand of tributaries of the South River, Augusta County, Virginia*

	North side tributaries				South side tributaries			
	A Mean of 20 samples	B Mean of 5 samples	Diff.	σ	A Mean of 20 samples	B Mean of 5 samples	Diff.	σ
Opaques	53.8	57.0	+3.2	5.0	44.6	44.2	− .4	6.05
Zircon	26.0	24.1	−1.9	4.4	26.0	24.8	−1.2	5.72
Tourmaline	11.7	10.1	−1.6	n.d.	15.6	16.5	+ .9	n.d.
Rutile	2.6	2.7	+ .1	n.d.	2.1	1.8	− .3	n.d.
Epidote	3.2	3.0	− .2	n.d.	9.7	10.8	+1.1	n.d.
Heavy residue % by weight	0.56	0.56	—		2.8	3.7	+1.7	

A = mean of all the samples collected from the respective sides.
B = mean of all first samples collected from each tributary on the respective sides.
σ = standard deviation; mean of all determinations for north side and for south side tributaries.
n.d. = not determined.

gether with the varieties of zircon as additional mineral species, statistically significant differences were found. Thus, although the analysis of variance for the opaques did not give any significant difference in contents of the two sets of tributaries on a number percent basis for the components examined, when the figures were converted to weight, the difference was highly significant at the 0.5-percent point. There is no significant difference in the total zircon as number percent, but a highly significant difference at the 1-percent point when the actual weight of zircon in the sands is considered. Furthermore, Type 1 zircon, well-rounded colorless grains, showed a significant difference at the 5-percent point in distribution between the tributaries. There is also a significant difference at the 5-percent point in the amount of heavy residue found in the 0.12- to 0.06-mm grade of these sands.

Another result is that detailed planned sampling in any small area will provide a set of constants, either the variance or the standard deviation, which will be of use in assigning samples of unknown origin to their correct place. For example, if detailed sampling is done on a formation of known age and then the mineralogical composition is obtained with the variance and standard deviation computed, then samples from a much larger area may be assigned to the known assemblage with confidence. This points to a very important way in which statistics can assist heavy-mineral studies.

The importance of the quantity of heavy minerals in sands has often been overlooked, but it is an attribute that can very easily be obtained. Grain counts alone are not enough and the weighting given to the amount of the individual grains is important. Table 10 shows that in locality 12 the quantity of opaques is very much greater than in any other sample, but from the grain counts the percentage in the population is quite average. In this same locality the percentage of zircon by grain counts is small compared with the majority of the samples, and yet when the weight of zircon in grams is used the contribution of zircon by this stream sand is found to be very near the average.

From the statistical examination of the results of grain counts a number of features of these residues have been emphasized, the principal one being, perhaps, that of the complexity of the residues coming from the Blue Ridge rocks compared with those of the Ordovician and Cambrian. This is shown in figure 4 where each of the south side streams is shown to have a slightly different mineralogy.

In this paper only a few aspects of the distribution and composition of the heavy mineral assemblages have been discussed. The statistical analyses have themselves shown a number of additional points to be examined, and a clear picture of the sampling plan for similar studies has emerged. It is hoped that

this investigation will prove of value to other workers contemplating similar studies with heavy minerals.

ACKNOWLEDGMENTS

My thanks are due to a number of people who have helped in various stages of this investigation. The scope and sampling were planned in consultation with W. C. Krumbein, Northwestern University, formerly with the U. S. Geological Survey, who has in addition offered much helpful advice in working out the statistical analyses of the data. John C. Hathaway, Geological Survey, helped locate the sampling sites in the South River valley. The samples were collected with the help of John T. Hack, Geological Survey, and W. H. Clatworthy, at that time with National Bureau of Standards; the latter also suggested the method of grain counts. Sample preparation and bromoform separations were done by Gillison W.Chloe, Geological Survey. W. S. Connor, National Bureau of Standards, assisted by setting out a suitable form for the analysis of variance in the nested design used and was consulted a number of times about the results of the analyses. The author is, however, solely responsible for any errors that may be found in the statistical analyses or in their geologic interpretations.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 57, NO. 4, PP. 405–416
FIGS. 1–6, DECEMBER, 1957

LITHOLOGY, WITH PARTICULAR REFERENCE TO CEMENTATION, OF UPPER CARBONIFEROUS SANDSTONES IN NORTHERN DERBYSHIRE, ENGLAND[1]

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ABSTRACT

The mineralogy and texture of the coarser clastic sediments exposed in a 940 feet long core at Smeekley in northern Derbyshire indicate that they are orthoquartzites with subordinate subgreywackes. The most abundant cement is quartz which was precipitated contemporaneously from the dominantly acidic waters at the site of deposition. Calcite, the second most common cement, was a primary precipitate in some cases but, together with kaolinite, has been partially redistributed later. Small, discrete pockets of primary chalcedonic silica and sericitic mica (?illite) also occur. At irregular intervals, the prevalent acid depositional conditions were locally modified probably by decomposing organic matter, to give conditions suitable for the precipitation of the calcite and siderite. Subsequent limonitisation of the siderite is the only mineralogical change which has been effected since the deposition of the sediments.

INTRODUCTION

In the post-war years systematic boring into the Upper Carboniferous strata of the British Isles has become commonplace. The main objects of the borings have been to prove the local stratigraphic sequence and assess the quality of any coal seams penetrated. As a result of this policy there have become available for lithological study a whole series of cores in which the beds are practically unaffected by surface weathering and from which have been acquired data having a significant bearing on their lithology and cementation. One such core, occurring at Smeekley (Nat. Grid 43/298765) in northern Derbyshire (fig. 1) and extending through a thickness of nearly 1000 feet of strata was selected for a systematic examination, particular attention being paid to the sandstones. They are mainly orthoquartzites ranging in age from the R zone of the Millstone Grit to the top of the *Anthraconaia lenisulcata* zone of the Lower Coal Measures and are interbedded with laminated siltstones, thin coals, seat-earths and shales (fig. 2). Characteristically, the sediments illustrate the effects of rhythmic deposition and within the Lower Coal Measures alone seven cyclothemic units have been recognized (Eden, 1954, p. 81) the bottom of each unit either being taken at a marine band, coal seam, or seat-earth. At least three similar units occur in the underlying Millstone Grit.

One of the main purposes of this paper is to draw attention to the cementation of the sandstones and its possible implications, both of which have been overlooked by earlier workers. The relationships of a whole range of cementing agents with clay minerals, quartz, and calcite predominating suggest that cementation was an early

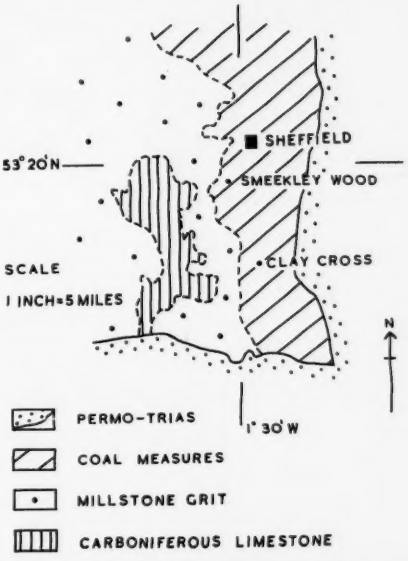

FIG. 1.—General stratigraphy of area and site of boring.

[1] Manuscript received January 24, 1957.

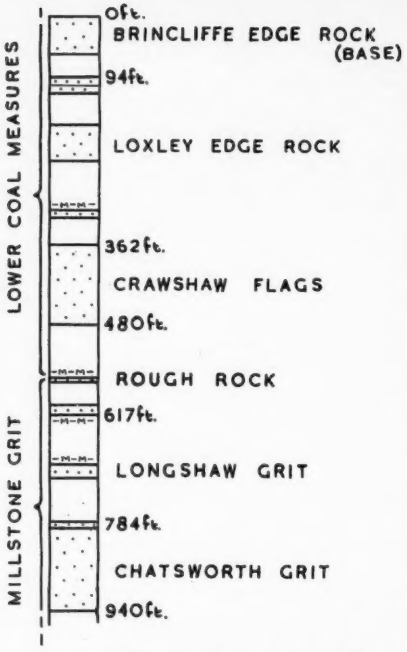

FIG. 2.—Sequence of strata penetrated by boring.

diagenetic effect and that little modification has subsequently taken place. As kaolinite, authigenic quartz, and hydrobiotite are quite common it also appears probable that the environmental conditions were essentially acidic in nature, at least towards the base of the transporting waters.

REVIEW OF LITERATURE

Although there is quite an extensive American literature on the lithology and more particularly the cementation of sandstones (Gilbert, 1949, Goldstein, 1948, and others) very few analogous studies have been attempted in Britain. The various observations regarding cements in the Millstone Grit and Lower Coal Measures, for instance, have invariably been incidental to the petrography of the more obvious and generally dominant clastic grains, although heavy minerals have attracted some workers (Sorby, 1859, Gilligan, 1920, and Butterfield 1937). One of the earliest notes on cements dates back to Phillips (1881, p. 11) who observed that "a considerable number of sandstones belonging to the Carboniferous period are composed of quartz crystals which have evidently crystallized 'in situ', since they exhibit the freshness of outline peculiar to crystals which have not been subjected to the slightest amount of abrasion subsequently to their formation." Sorby (1908) made reference to the solution of feldspars and subsequent precipitation of kaolinite in pore spaces in a discussion on the decrease in angles of dip of fore-sets during lithification, and his hypothesis was upheld by Kendall and Wroot (1924, p. 113–114, 119–120) in their summary of Yorkshire geology. The two latter workers likewise suggested that some of the silica released during the solution of the feldspars was reprecipitated on the clastic quartz grains with the formation of triangular facets.

In the interim period between the broad summaries given by the above, a series of papers on the Millstone Grit of northern England were published by Gilligan (1915–16, 1919, 1920). These brought to light the association of calcite and decomposed feldspar (1915–16, p. 15) together with the fact that calcite was locally abundant as cement in the Rough Rock of the Meanwood district of Leeds, Yorkshire (1920, p. 267). At other sandstone horizons Gilligan observed a lack of abundant calcite: "It cannot be said that calcite commonly acts as a matrix to the grit; and it has not been found in any quantity. . . " (1920 p. 267). Apart from recording barytes in the Kinderscout Grit of Wharfedale and kaolinitization in the Rough Rock of Horsforth no further reference to cementing agencies was made. It is interesting to note that the kaolinite was considered as being formed by the exposure of the Rough Rock in post-Carboniferous times, a time of origin much later than that postulated by Sorby, Kendall and Wroot.

The first specific but brief incursion into the study of Coal Measure cements was by Carruthers (1923) who investigated the Rotherham Red Rock and concluded that the consistent red coloration was mainly due to haematite of contemporaneous origin. He was followed by Lewis and Rees (1926) who thoroughly examined the Wickersley, Ackworth, Brincliffe Edge, and Loxley Edge Rocks in the neighbourhood of Sheffield. They found the cements relatively

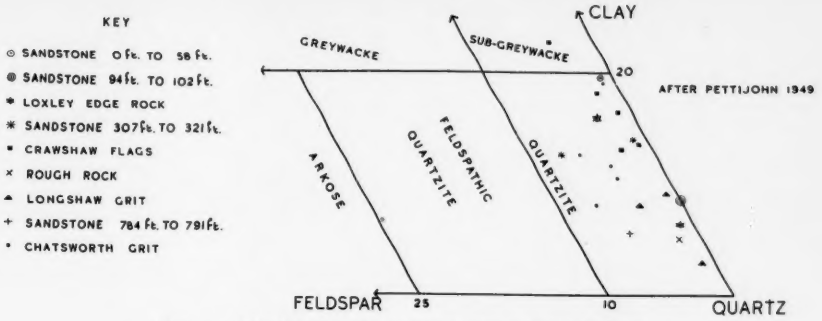

FIG. 3.—Classification of sandstones from selected horizons.

uniformly distributed in all the above sandstones. The secondary authigenic outgrowths on clastic quartz grains were thought to be due to the precipitation of silica derived from the breakdown of feldspar and mica. Limonite, having aggregate grain sizes up to 0.50 mm in diameter, was probably detrital in part, the remainder being formed from decomposing biotite, siderite, or pyrites. At all horizons, chloritic minerals and sericitic mica were disseminated throughout the matrix and in the Brincliffe Edge Rock, barytes was recorded. Kellett (1926) found that siderite was common in the Coal Measure sediments of Durham and two important contributions on its mode of origin in the Yorkshire coalfield came from Deans in 1934 and 1935. He concluded that of the two widespread forms of siderite found, the spherulitic was secondary in origin and the non-spherulitic (as in clay ironstones) primary.

Butterfield, in a number of investigations between 1934 and 1939, also noted the presence in quantitity of siderite together with dolomite and magnesite in Millstone Grit sandstones near Yeadon, Yorkshire (1937). Since that period the most pertinent contribution to this subject has been from Dunham (1953, p. 111–118) who, in the Geological Survey Memoir of the country between Bradford and Skipton, Yorkshire, described in considerable detail selected sandstones from various horizons within the Millstone Grit and Lower Coal Measures. Excluding carbonaceous matter, the main cementing materials were secondary quartz, calcite, limonite, kaolinite, and probably illite. Small amounts of siderite, dolomite, ankerite, and magnesite were also present. In the case of the Whinny Hill Brick Pits quarry (1953, p. 112) he noted that "while the rock is cemented with secondary silica in places, it appears to owe its consolidation mainly to the close packing of the quartz grains. . . ." At some horizons, e.g. Skipton Moor Grit, the cement was dominantly calcite forming approximately 37 percent by volume of the rock, whereas at others, interstitial mosaics of kaolinite were present. It is significant that the irregular pockets of kaolinite often abutted against fresh feldspar grains indicating an origin not involving a breakdown of feldspar "in situ." Dunham's ultimate conclusion (1953, p. 117) was that, with the exception of the ferriferous carbonates, the sandstones examined gave "little or no support for the view that extensive chemical changes have occurred . . . since they were laid down." He attributed the limonitisation of the iron carbonates to superficial changes.

SANDSTONES

General Petrography

Only the clastic sediments with median grain sizes greater than 0.06 mm. are considered in this paper, the median diameters being obtained from cumulative curves based on thin-section analyses (Greenman, 1951). This lower limit conforms with that established by Wentworth (1922) for the division between siltstone and sandstone.

Considered as a whole, the sandstones investigated have a relatively narrow range in mineralogical composition. This is illustrated by selected samples in figure 3 (based on Pettijohn 1949, fig. 66) where the

three major constituents (quartz, feldspar, and clay) have been recalculated to 100 percent. It is clear that orthoquartzites are dominant although there is a tendency towards sub-greywacke in some cases which is more obvious from the textural point of view in thin section than figure 3 would suggest. It is also probable that the authigenic quartz growth on the clastic grains slightly emphasizes the orthoquartzitic tendencies.

The use of these two lithological terms, sub-greywacke in particular, is open to some considerable debate but is adhered to for convenience of comparison with standstones similarly classified elsewhere (Scheere, 1954). From the genetic standpoint it is significant that the lithological association typical of unstable shelves includes quartzites and sub-greywackes together with silty shales, an ever present one throughout the sequence studied (Krumbein and Sloss, 1951). Thus it is inferred that sedimentation in Upper Carboniferous times in northern Derbyshire at least, occurred under conditions of moderate subsidence and relative instability, a conclusion which is borne out by older and current lines of research.

Two further interesting features are emphasized by figure 3 the first being the non-vertical or stratigraphical distribution of the rock types; the sandstones tending towards to the quartz pole are not confined to the Millstone Grit, neither are those tending towards sub-greywackes confined to the Lower Coal Measures. This lack of consistency of rock type with horizon paradoxically substantiates the view of the over-all similarity of conditions of deposition during the greater part of Upper Carboniferous times in the area. Secondly, the feldspar content is consistently low and varies from 0.5 to 7 percent by volume. Under the circumstances, to call the rocks arkoses (Gilligan 1920, p. 259) which, for classificatory and

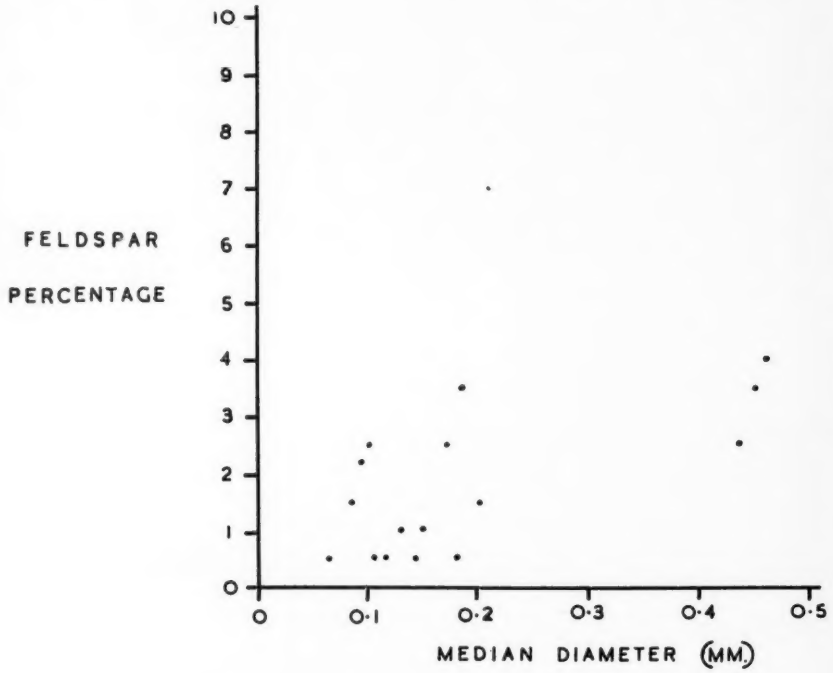

FIG. 4.—Relationship of total feldspar content to median grain size in the selected sandstones.

genetic reasons are now taken as having a feldspar percentage greater than 25 (Pettijohn, 1949, p. 257–261) is incorrect. Prior to the present day refinements in sandstone terminology it would have been natural of course to classify the rocks, especially those of Millstone Grit age, as arkosic because of their tendency towards a granitoid mineralogy.

At Smeekley, the sandstones are generally coarser grained in the Millstone Grit (median grain size ranges from 0.08 to 0.48 mm) than in the Lower Coal Measures (0.065 to 0.26 mm) although within each group coarser and finer facies are found which may be stratigraphically deceptive in surface mapping. Only a wider areal study can confirm whether this trend in grain size is indicative of tectonic adjustment within the source or depositional area. It is interesting to note, even with limited data, that the feldspar content only roughly increases with increase in median grain size (fig. 4). This general tendency was likewise recorded by Dunham (1953, p. 112) from the Skipton district of Yorkshire. That the relationship is not more precise may be due to variations in the supply of feldspar from the immediate source area. These variations are impressed on the abrasive and sorting processes normally attendant on material being transported by a fluid medium and account for the not entirely random distribution of points as plotted.

Specific Petrography and Cementation

In this section attention is mainly focussed on the nature, distribution, and relationships of the cementing agents with special emphasis on their order of deposition or precipitation. The rocks are dealt with in stratigraphic order, the oldest first, and the discussion relating to each can be considered as applying to the other beds under review unless otherwise stated. This avoids undue repetition.

The Chatsworth Grit. This zone extends from a depth of approximately 793 to 925 feet in the core (fig. 2) and it consists of a highly quartzose sandstone (median grain size varies from 0.08 to 0.48 mm) in which the quartz content fluctuates between 80 and 86 per cent by volume and the feldspar content never surpasses 7 per cent (fig. 3). The dominant cementing material is quartz, and the majority of the clastic quartz grains are modified in outline by this agent. There is no evidence for an interpenetration of the orginal quartz cores, and the interlocking and patchy orthoquartzitic texture appears to be caused solely by secondary enlargement (fig. 6B). It suggests that the rock, to a great extent, owes its consolidation to authigenic quartz cementation and not to original close packing of the grains; otherwise there would be a greater proportion of cores in contact with each other. From this, it is inferred that the quartz cementation was an early process in the lithification of this particular sandstone—probably contemporaneous or pene-contemporaneous—before undue compactive stresses had time to become operative. Dunham (1953, p. 112) indicated the apparent reverse relationship in sandstones of E age (lower Millstone Grit) at Skipton and in their case the consolidation appeared to be mainly due to the close packing of the grains prior to cementation.

Between the larger grains within the Chatsworth Grit occur irregular pockets up to 0.5×1 mm in size of a kaolinite-type mineral having a low birefringence (less than 0.0005), straight extinction, and exhibiting rouleau texture. The presence of kaolinite was later confirmed by Dr. G. Nagelschmidt using X-ray methods. As in the case of the Carboniferous sandstones studied by Smellie (1913, p. 268) the kaolinite sometimes abuts against perfectly fresh potash and plagioclase feldspars (oligoclase, andesine) which are intermingled with others showing partial sericitisation (fig. 5B). This relationship contradicts any suggestion of post-depositional kaolinitization of the feldspars although is is probable that some of the kaolinite is derived from their decomposition during transportation. Favouring this interpretation is the general absence of authigenic quartz growth where the kaolinite pockets are adjacent to quartz grains which indicates the co-deposition of clastic grains and the kaolinite. On rarer occasions a veneer of authigenic quartz is interdigitated between grain and cement implying a possible later migration of kaolinite in solution through available pores (Hemingway and Brindley, 1948).

A mineral having a higher refractive index and higher birefringence than kaolinite also

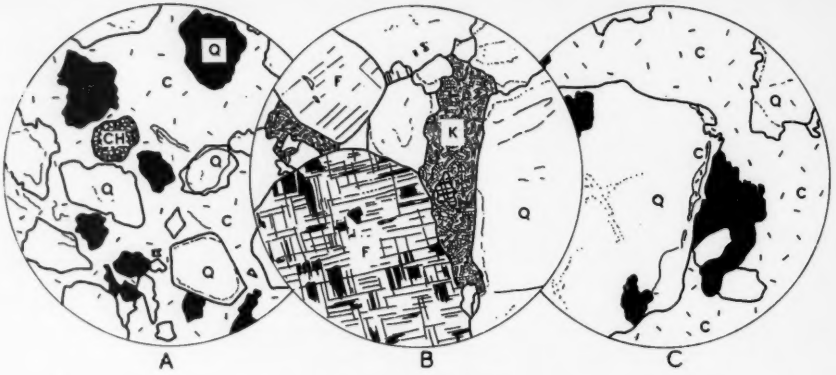

FIG. 5.—Crossed nicols.

A. Loxley Edge Rock. ×42. Corroded quartz (Q) "floating" in a calcite matrix (C). Some of the quartz grains show idiomorphic outlines due to authigenic growth. Note the ovate, uncrushed pocket of chalcedonic silica (CH).
B. Chatsworth Grit. ×42. Kaolinite rouleaux (K) abutting against fresh potash feldspar (F).
C. Quartzite at 784 feet. ×42. Calcite replacing quartz along a zone between the core and authigenic growth.

occurs in irregular pockets and may be a member of the illite group. The mineral, which resembles sericitic mica, has a more obscure paragenesis in that it appears to be the main decomposition product of the feldspars apart from being present in isolated pockets. In some instances there is a gradation from a near entirely altered feldspar into a pocket consisting entirely of the sericite-type mineral whereas, in other cases, its general relationship to the clastic grains is strictly analogous to that of the kaolinite described above. This evidence makes it probable that the deposition of the clastics and sericitic mica was contemporaneous in part, the source of the mica being the acid feldspars which presumably were altering during transportion or had altered prior to the erosion of the parent rocks. The presence of sericite flakes "trapped" between the core of a quartz grain and its authigenic veneer confirms this hypothesis.

Of minor importance in the cementation of the Chatsworth Grit are sporadic and small patches of chalcedonic silica, calcite ($\omega = 1.656$), and a brown iron oxide, limonite which is usually associated with a degradation product of biotite such as observed by Lewis and Rees (1926) in the Wickersley Rock and by Wager (1944) at Shap.

Sandstones between the Chatsworth Grit and the Pot Clay Marine Band (base of Lower Coal Measures). Resting immediately upon the Chatsworth Coal at Smeekley between the depths of 784 feet and 791 feet is a poorly sorted quartzite (median grain size 0.10 mm) in which are developed minor sedimentary structures (Greensmith, 1956). The dominant mineral cement is calcite ($\omega = 1.658$) together with subordinate ankerite ($\omega = 1.698$) but they are rather obscured by abundant dark carbonaceous matter concentrated into irregular horizontal laminae. Within these laminae there is invariably a limonite (after siderite)-hydrobiotite association. The quartz grains commonly show incipient corrosion and the acid plagioclases (oligoclase, andesine) are sometimes replaced along twin zones and cleavages by the calcite (fig. 5C). The former are mainly subrounded and only rarely develop authigenic outgrowths but where they do, it is the new growth which tends to be corroded by the calcite. The enlargement very rarely gives rise to pronounced idiomorphic outlines, but where it does the implication is adequate pore-space into which the re-forming grain could grow. It also suggests that the precipitation of the calcite occurred after the precipitation of the quartz. Intermingled with them are subordinate kaolinite, chal-

TABLE 1

	Depth (ft.)	Clastic Quartz	Organic C	Sulphur
Cancellatum M.B.	687′6″	3.3%	4.53%	9.27%
	689′6″	17.1	3.09	5.22
	690′	40.5	1.24	3.99
	691′6″	65.2	0.64	1.47
Longshaw Grit	694′	87.5	0.14	0.85

cedonic silica, and sericite flakes in the form of irregular interstitial pockets.

The Longshaw Grit (median grain size varying between 0.11 and 0.43 mm) is approximately 24 feet thick and lithologically is a quartzite (fig. 3). At the top there is distinct evidence of "fining" upwards over a thickness of 6 feet into silty shales of marine character i.e., the Cancellatum Marine Band, with angular quartz grains up to 0.04 mm in diameter. A series of clastic quartz determinations and partial chemical analyses through this section emphasizes the grading and moreover suggests that it was caused by a progressive decrease in the transporting power of the waters and not a turbidity current (table 1). The relatively well-sorted nature of the sandstone substantiates this conclusion.

The cementation through the Longshaw Grit proper is patchy though calcite-rich laminae ($\omega = 1.658$) with subordinate dolomite ($\omega = 1.680$) predominate towards the top and base. In these more calcareous zones both the acid feldspars (microcline, orthoclase, oligoclase, and andesine) and the quartz grains (some with pronounced euhedral outlines caused by new growth) show extensive corrosion. Residual calcite granules "trapped" between the original cores of quartz and their outgrowths never appear, which favors the pre-carbonate precipitation of quartz. The recurrent association of corroded feldspar and calcite was noted by Gilligan (1915–16, 1920, p. 262) in the Rough Rock at Meanwood.

A peculiar property of many of the clastic grains within the calcite-rich laminae is that they seem to be "floating" in the matrix. This characteristic, which is difficult to assess in the two dimensions essentially offered by a thin section, must be treated with caution. Nevertheless, at the Longshaw Grit and higher stratigraphic horizons, there is little doubt that the phenomenon occurs. An explanation merely involving the redistribution of calcite by circulating ground waters is far from convincing for these distinct zones although it may be appropriate for isolated patches. Thus, two other modes of origin have been considered. One involves the isolation of the grains by corrosion of which there is ample evidence and the other involves simultaneous precipitation of calcite from the transporting waters. On the whole, the evidence supports the second interpretation in preference to the first since not only are some of the grains considerably isolated, but those that are still retain a veneer of authigenic quartz. It follows by accepting this second hypothesis that at least a part of the authigenic quartz deposition must have occurred during transport. There is no factor in favor of a post-calcite precipitation of quartz.

A less conspicuous cement in the Longshaw Grit is chalcedonic silica which is found in small, highly irregular pockets and shows no distinct relationship to the other cements. Only at one horizon is there a suggestion that the calcite is replacing the chalcedony. Of lesser importance are kaolinite and sericitic mica which have similar relationships to those in the rocks described earlier.

Between a depth of 604 feet and 610 feet are sandstones in which are intercalated laminated coarse siltstones. The lamination is an expression of variations in grain size, mineral cementing agents and carbonaceous matter. The last two factors are the most important as the range in median grain size of the sediments from 0.059 mm to 0.110 mm is not wide. In the lighter grey laminae, the main cement is usually either authigenic silica or calcite with subsidiary kaolinite and sericite. Corrosion and "floating" grains (about 10 percent by volume) are present in some of the calcite-rich zones. The tenuous light brown to black laminae are due to an association of opaque carbonaceous matter, limonite, siderite ($\omega = 1.874$), hydrobiotite,

and muscovite (fig. 6A) and this concentration of carbonaceous matter and large mica flakes (up to 0.10 mm long) implies low current velocity immediately above the depositional interface whereas the larger randomly distributed clastic grains, which appear to be "floating" were probably deposited from more agitated waters nearer to the surface. The origin of the limonite is twofold, some being derived from biotite decomposition and the rest by the secondary alteration of the siderite. Its presence results from the only process which can be definitely established as secondary in the cementation history of these rocks and it must have formed at some period when the local permanent water-table was abnormally low. It is very doubtful if any of the other cements have been affected.

Lithologically the next higher sandstone in the sequence i.e. the Rough Rock (fig. 2) is a quartzite (median grain size 0.20 mm), and the dominant cement is quartz with subsidiary calcite ($\omega = 1.658$), dolomite ($\omega = 1.680$), chalcedony, and kaolinite. There is no interpenetration of the original cores of the quartz grains and both the acid feldspars and quartz show corrosion to some degree wherever they are in contact with calcite.

Sandstones of the Lower Coal Measures. For the present purpose, the sandstones above the Pot Clay Marine Band (556 feet in core) can be treated as a whole because they repeat most of the features found in the Millstone Grit sandstones. The Crawshaw Flags (median grain size varies from 0.08 to 0.18 mm) occurring between the depths of 362 and 480 feet are partially sub-greywacke in character with authigenic quartz, kaolinite, and sericite as the main cements. Small amounts of chalcedony, calcite, and chlorite are usually present together with tenuous carbonaceous films rich in limonite.

They are similar in most respects to the Loxley Edge Rock—175 to 229 feet—except that the latter rock (median grain size 0.09 to 0.26 mm) has more calcareous zones in which the apparent percentage of "floating" grains reaches 30 by volume occasionally. Small flakes of muscovite show considerable distortion within these zones probably as a result of the early crystallization of the calcite. At one horizon—194 feet—pockets of chalcedonic silica abut against authigenic idiomorphic faces on quartz grains suggesting new growth prior to the deposition of the chalcedony. The generally irregular nature of the pockets also leads to this conclusion yet, if the deposition was in primary gel-like form its irregular nature could be accounted for by compaction processes alone and new quartz growth could have developed whilst the grains were in contact with the soft colloidal matter. Therefore, most if not all the chalcedony is possibly primary and it is particularly pertinent to record that within the calcite-rich zones, pockets of chalcedony occur up to 0.20 mm across of

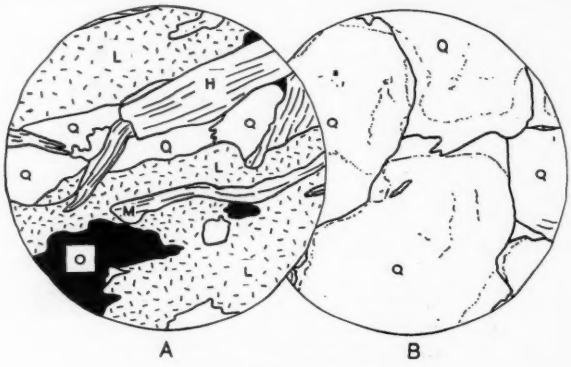

FIG. 6.—Plane polarized light.

A. Sandstone at 604 feet. ×250. Thin lamina showing assemblage of carbonaceous matter (O), hydrobiotite (H), muscovite (M) and limonite (L) with detrital quartz (Q).

B. Chatsworth Grit. ×42. Quartzitic texture developed by authigenic quartz outgrowth without penetration of the original cores.

TABLE 2.—*Cements and order of cementation*

Contemporaneous	Quartz	Chalcedony	Calcite	Siderite	Kaolinite	Sericite
Pene-contemporaneous	—	—	Calcite	—	Kaolinite	Sericite
Secondary	—	—	—	Limonite	—	—

relatively uncrushed nature (fig. 5A).

The youngest sandstones (fig. 3) are only of interest in that between a depth of 94 and 102 feet is a quartzite in which the cementation by quartz in optical continuity is particularly evident. The presence of a sandstone having this composition and texture at such a high horizon in the core is significant when the source of the silica in solution is being traced and will be discussed later.

In summarizing all the evidence presented above it is concluded that three phases can be recognized regarding the cements and their order of precipitation (table 2). The authigenic quartz, which is the most abundant cementing agent, was precipitated contemporaneously as was the calcite (the second most abundant) in some cases. Wherever these two cements are intimately associated the precipitation of the quartz preceded that of the calcite.

Of little importance volumetrically are chalcedony, kaolinite, and sericite, all of which are found in small pockets but which nevertheless were deposited at the same time as the clastic debris. The last two may have undergone slight mobilization and re-formation during the earliest stages of diagenesis prior to the removal of the sediment from the influence of the transporting waters. Some of the calcite may likewise have been affected. Siderite, probably a primary precipitate, is only common in thin carbonaceous laminae but its influence is evident throughout the rocks examined due to limonitization during late diagenesis, the limonite having been subsequently partially redistributed.

SOURCE OF CEMENTING MATERIALS

It is probable that sericite formed from the breakdown of feldspar during transport from the source area. Similarly, the kaolinite is probably a more advanced decomposition product of feldspar and during its formation silica would be released into solution, later to be partially deposited as chalcedonic silica. The possible sources of iron in solution have been adequately discussed by Taylor (1949, p. 77–80) and his view is adopted that iron is so widespread a constituent of the earth's crust that any specific hypothesis hardly seems necessary. The decomposition of biotite during transport would release and account for some iron in solution. Calcium and carbon dioxide must likewise have been widespread in the waters as they are at the present day, to explain the distribution of calcite. Possibly they could have been partly derived from the solution of calcareous organisms buried within the sand but, as no fossil fragments remain, it is more likely that they were brought in from external sources which could have been either organisms or, in the case of the carbon dioxide, decaying vegetation. There is no evidence for the deposition of non-organic clastic carbonate fragments capable of recrystallizing as a cement.

The precise origin of the silica now forming authigenic outgrowths on the clastic quartz grains is also conjectural. As in the instances of iron and calcium, silica is normally abundant in stream waters and, at the present day, it is estimated that approximately 319 million metric tons of silica are transported to the sea annually in that manner (Twenhofel, 1950, p. 398). It is highly likely that the decomposition of feldspars and micas accounted for part of the silica in Upper Carboniferous times but little can be inferred beyond that. There is nothing to suggest that the silica was derived from the clastic quartz by a mechanism involving the crushing of the grains together and solution at their points of contact (Waldschmidt, 1941; Pye, 1944). The cores of the grains do not show interlocking and no stylolitic junctions are present which ought to be expected if solution by pressure was an operative and effective process (Goldstein 1948). An implication of the pressure-solution hypothesis of Waldschmidt is that the basal sandstones within any given group of sediments should be more quartzitic than the upper due to greater superincumbent load. This is not substantiated at

Smeekley where greater and lesser quartzitic zones are randomly distributed throughout the core.

CONDITIONS OF DEPOSITION OF THE CEMENTS

The main implication of the data recorded above is that the waters in which sedimentation was occurring were dominantly acidic in nature. At the site of deposition and particularly immediately above the bottom, they must have been so and it follows that the waters carrying their load into the area were probably acidic to some extent, although the evidence for this is naturally more tenuous. Clearly this hypothesis only specifically applies to the sandier facies; the shales may require a modified interpretation.

The presence within the sandstones of a range of products derived from the decomposition of biotite is normally a result of reaction with peaty, acid waters (Wager, 1944). It is also significant that the solubility of silica decreases appreciably under acid conditions and presumably is more likely to be precipitated either as quartz and chalcedonic silica or in combination with other elements. This idea of primary precipitation is nothing new. Krynine, Honess, and Myers (1941), for instance, thought that co-deposition of silica and clastic sand grains was a distinct possiblity in the case of Upper Cambrian beds in Pennsylvania. The deposition of silica from circulating connate or meteoric waters is thought, on the other hand, to be most unlikely. Confirmation of primary precipitation comes from the work of Correns, Barth and Eskola (1939) on modern sedimentation, from which they concluded that in environments where the pH is less than 5 any silica in solution is precipitated immediately, whereas any Al_2O_3 tends to remain in solution. With decrease in acidity—pH 5 to 9—silica is less and less likely to be precipitated and at pH values above 9 both silica and alumina are highly soluble. Therefore, they suggested that at low pH values, kaolinite is the clay mineral most likely to be formed and preserved. The joint presence of authigenic silica and kaolinite within the Millstone Grit and Lower Coal Measures can thus be explained in terms of acid waters though the exact mechanism of silica precipitation is still open to some doubt. Regarding this problem, it has been pointed out by many workers (Wells, 1955; Rankama and Sahama 1950) that present day sea-water contains only a very small proportion of silica. Approximately 99 percent of the silica transported by streams is believed to be precipitated where they disgorge into the oceans and the suggestion is that the silica is deposited in gel-like form on the sea floor mainly by electrolytic flocculation. Sargent (1923), for example, thought that some cherts may have formed in this way, the gel being deposited off the mouth of large rivers flowing into shallow epicontinental seas. By analogy, it may be possible that the Smeekley sandstones were laid down under similar environmental conditions but a consideration of the non-colloidal form of most of the precipitated silica together with the incurred low volumetric increase in quartz content of the rocks (about 2 to 3 percent) make it doubtful if a similar mechanism of precipitation or environment of deposition is a valid inference.

There are many indications that the pH of the waters was delicately poised. The calcite-rich zones are significant pointers in this respect as they imply that alkaline conditions must have prevailed on the bottom occasionally. Correns (1950) examined the mechanism of precipitation of either calcium carbonate or silica in the presence of each other and worked out the following pertinent chemical equations:—

$$(CaCO_3)+H_2SiO_3+H_2CO_3 \rightleftharpoons Ca^{++}+2HCO_3^-+H_2O+(SiO_2)$$

$$H^++HSiO_3^- \rightleftharpoons SiO_2+H_2O$$

$$(CaCO_3)+Na_2SiO_3+3H_2CO_3 \rightleftharpoons Ca^{++}+4HCO_3^-+2Na^++(SiO_2)$$

These reactions, where $CaCO_3$ is precipitated and SiO_2 dissolved (and vice versa) are pH dependent, only the $CaCO_3$ being deposited under alkaline conditions and SiO_2 under acidic conditions. The incipient corrosion of quartz by calcite is probably a manifestation of this reaction and, as a fluid medium is essential, it is probable that the replacive relationship is an early diagenetic one although post-dating the precipitation of the silica. It also seems reasonable to suggest where modified quartz grains are

"floating" in a carbonate matrix that the new outgrowths developed during transit in the acid waters. Then the enlarged grains and carbonate were laid down in a pocket of comparatively high pH.

The reason for the localized pockets of alkalinity and consequent formation of carbonate-rich zones with "floating" clastics is rather elusive. The breakdown of calcareous organisms and subsequent reprecipitation of carbonate "in situ" is unlikely although it is possible that breakdown elsewhere could account for some of the calcium and carbon dioxide in solution. Probably the answer relates to the carbonaceous (plant) matter which is present in variable amounts, either as discrete particles or tenuous laminae, throughout the sandstones. The decomposition of the more nitrogenous material might lead to a local reversal of the prevalent acid water conditions by the evolution of amines or amides and calcite could then be precipitated. This mechanism also satisfactorily explains the common association of siderite and tenuous carbonaceous zones (Weeks, 1953, p. 171). The fact that siderite and not calcite was deposited probably shows that the concentration of ferrous ions in solution was locally higher during the time of precipitation or that the carbon dioxide in solution had been depleted (Moore and Maynard, 1929). In either case, siderite is less soluble than calcite in acidic waters and probably would tend to be deposited first providing there was sufficient iron in solution. Other possible mechanisms of siderite precipitation have been fully reviewed by Taylor (1949, p. 81–84) but none in which the mineralogical assemblage described above has appeared. "Floating" quartz grains and pockets of chalcedony in the carbonaceous zones were probably carried in by the surface water layers of less alkaline nature.

SUMMARY

In conclusion it need only be reiterated that the sum total of this new evidence, mainly deduced from the cements, strongly indicates a dominance of acidic waters at the site of deposition. From the environmental viewpoint this hypothesis is important in that marine waters at the present are predominantly alkaline. Its implication of deposition and probable transport under non-marine conditions in so far as the coarse sediments are concerned elegantly substantiates Gilligan's deltaic environmental hypothesis (1920, p. 276) for the Millstone Grit of northern England and suggests that similar circumstances probably prevailed in northern Derbyshire at least into Lower Coal Measure times.

ACKNOWLEDGMENTS

The author would particularly like to thank Professor L. R. Moore for supervising this work carried out in the Department of Geology at Sheffield University and critically helping in the discussion and manuscript phases. He is also grateful to Professor K. C. Dunham and Dr. J. F. Kirkaldy for reading through the paper and making constructive suggestions regarding the presentation of the data. Dr. G. Nagelschmidt kindly helped with the identification of the clay minerals.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 4, PP. 417–420
DECEMBER, 1957

COMBINED PREFERENTIAL STAINING AND CELLULOSE PEEL TECHNIQUE[1]

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ABSTRACT

Minerals in exposed thin-sections, diamond-sawed slabs, and detrital minerals partially embedded in mounting media can be preferentially stained with various dyes, and cellulose peels can be obtained from these materials to show both fabric and discrete mineral species. These have the advantage of providing inexpensive "copies" which can be utilized in projection, microscopic examination, and in some instances in preparation of photographic illustrations. They can be readily filed for ready reference in a small storage space, are practically indestructible in routine work, and last indefinitely.

INTRODUCTION

Stains have been described for many minerals, and numerous techniques are described in the literature of preferential staining in rock slices, thin sections, crushed fragments, and detrital grains. Workers in sedimentary petrology and petrography have utilized various techniques to etch rock surfaces and exposed thin-sections in order to obtain cellulose peels. The writer was made aware of some of the peel techniques 25 years ago in courses in Botany and Paleobotany. During the past few years successful application of combined preferential staining-cellulose peel techniques were made in connection with research and graduate courses in sedimentary petrology and petrography at Brigham Young University. However, more recent investigations, not only with sedimentary rocks, but with igneous, metamorphic, and granitized rocks at the University of Washington[2] have also yielded satisfactory results. Some of these investigations are those of the writer only, and some are research studies and routine laboratory exercises of students in graduate courses in petrology and petrography. This short note describing the technique is, therefore, the outgrowth of studies made in an attempt to arrive at rapid and accurate laboratory investigations of minerals, rock fragments, thin-sections, and lapped surfaces of rocks.

[1] Manuscript received March 26, 1957.
[2] Visiting Professor of Geology (on leave from Brigham Young University).

TECHNIQUE

Rock specimens and samples are readily studied by working with diamond-sawed surfaces. Depending upon texture (grain size and crystallinity) the surface can be further lapped with 220- or 400-mesh grinding powder. The rock surface is then washed clean and dried. If the specimen contains carbonate minerals, and it is desired to distinguish one mineral from the others by utilizing stains (following a brief etching in HCl, rinsing, and drying), one of the standard methods is used (Boswell, 1933, pp. 213, 220–21, 258–59, 268, 272; Holmes, 1930, pp. 261–82; Heinrich, 1956, pp. 7–8). If the rock is sedimentary and belongs to the arkose clan or graywacke clan, and only total feldspars are to be stained, the momentary etching with hydrofluoric acid (in a fuming box, or by contact with the acid) followed by gentle rinsing in water and staining with a dye such as malachite green, is utilized. Should one desire to distinguish potash feldspar in the exposed surface (or among detrital minerals partially embedded in balsam, Lakeside cement, Aroclor, or gelatin), the Cobaltinitrite stain is applied to the gel produced by the acid, and a brilliant yellow color results. Similarly-stained feldspars among igneous, metamorphic, and granitized rocks obviously will respond to this technique. Furthermore, the presence of ferruginous material in some rocks, such as in alternating layers of oolites, and pisolites, can be distinguished by certain alkali thiocyanate stains. When the desired color (or colors when combinations of stains are

made) is finally achieved to identify mineral species, a solution of cellulose peel is applied. Some stains require "fixing" in ammonia or other material prior to application of the cellulose solution. The writer has found the following solution ("recipe" suggested to him by Professor J. Keith Rigby of Brigham Young University) most useful:

Parlodion	112 gm
Butyl Acetate	1000 cc
Amyl Alcohol	40 cc
Xylene	40 cc
Ethyl Ether	12 cc
Castor Oil	12 cc

This type of peel solution possesses numerous advantages over certain others the writer has tried, chief among them being the high degree of flexibility (with no brittleness), relative safety near heat, and clarity of the final product. A stock solution is stored in a cool dark place; a smaller quantity is kept in a bottle having a type of lip which permits smooth pouring of the solution without admixing air bubbles and without undue dripping.

The rock or mineral specimen which was previously stained and dried is now placed so that the upper surface is flat. Slowly apply the cellulose peel solution but do not stir or agitate. The surface to which the cellulose is applied should be dry but not warm, otherwise bubbles will form. Do not attempt to dry on a hot plate or oven, but "cure" or dry in a ventilated area free of dust and strong air currents. If a thick peel is desired, apply a second coat a few hours after the first. Allow the specimen to "set" for 12 to 24 hours (normally overnight is sufficient) before removing the peel. The writer has found that by loosening the periphery of the cellulose with a razor blade, the peel can then be removed slowly by beginning at one edge and gently pulling and lifting; thin peels tend to tear, but by utilizing the razor blade at tenacious areas generally the complete cellulose can be removed undamaged. Experience will soon teach one to control the thickness of the peel and other variables. The degree to which the cellulose has picked up the color of the stain as well as the fabric of the treated specimen depends in large measure upon the following: 1) intensity of etching prior to application of the stain; 2) whether the dye was adsorbed or absorbed in the carbonate or ferruginous material or the gel of the feldspar; 3) tenacity of rock (e.g., friable, etc.). Peels can be obtained from certain weakly-cemented arkoses, subgraywackes, and other arenites which will have not only an impression of the fabric, but actual stained and unstained mineral grains and rock fragments embedded in the cellulose. Obviously, certain advantages incident to microscopic study, projection, copying, etc. are realized from such peels.

The writer has found that the cellulose mixture itself is an ideal embedding medium for some detrital and crushed minerals and fragments. A much thinner mixture than the stock solution is used (by diluting it with acetone). This is poured upon the surface of a flat-lying glass (such as a petrographic or biologic slide, a $2'' \times 2''$ slide, or lantern-slide glass), and when the mixture is partially set the detrital minerals or crushed materials are sprinkled upon it. When the cellulose hardens, the sample can be stained or studied as is. In some instances it may prove desirable to stain certain mineral species, then pour on the regular cellulose mixture, and either remove the peel when the material has set, or to place a cover glass (such as another $2'' \times 2''$, or lantern-slide glass) upon the upper surface of the partially gelled cellulose, and thus have a more or less permanent mount. Or, Permount can be applied as either the cover glass, or as the cementing medium for the cover glass instead of another cellulose coating. The unpeeled slides can prove useful in microscopic study or in projection, in either transmitted or reflected light.

A useful variation of the method involves embedding the detrital minerals or crushed materials in formalin-softened gelatin which was previously spread on the glass surface. After this mixture has dried the grains and /or fragments can be examined in immersion oils progressively of varying index of refraction by washing one oil from the slide with alcohol or carbon tetrachloride before applying the next index oil, thus keeping the fragments intact with their original orientation. Professor C. T. Bressler of the University of Oregon has pointed out to the writer (oral communication) that he and some of his graduate students are using a

modification of the Marshall and Jeffries' method (Soil Science Proc., Vol. 10, pp. 397–405) of examination of mineral grains in immersion oils that has proved very successful. The writer has noted however, that if stains are applied to grains or fragments so embedded in formalin-softened gelatin, greater care must be exercised in applying the stain, washing and drying, to prevent loss of sample. When the material is dry, the cellulose peel solution is applied in the usual way, and when it has set it can easily be removed. Normally all the grains will adhere to the cellulose, but this has the advantage of retaining each grain in its orientation as identified in immersion oils.

APPLICATIONS

Petrologists and petrographers who find cellulose peels a helpful complement to field and laboratory studies, naturally should find useful application of the combined stain-peel technique. Petrographers invariably face the dilemma of having numerous fine hand-specimen-size (or larger) rocks which they collected, but cannot afford the time and money to prepare large-slice thin-sections. It is a relatively simple matter to cut slices, slabs, or pieces from these large specimens with a diamond saw. Also, petrographers who grind standard size thin sections, and/or $2'' \times 2''$ slides and lantern-slide size slices, may desire to obtain a few "copies" of fabric and mineralogy prior to placing the cover glass. Seldom would one have to stain a rock slice that is to be covered. Normally the rock surface from which the slice was obtained would provide enough working area for staining and obtaining a peel. Furthermore, the sawed surface can repeatedly be re-stained, as each succeeding peel might remove most of the dye. The writer has found that one encounters specimens from which it is desirable to obtain stained peels of varying thickness, depth of color, or intensity of fabric. This is true of some carbonate rocks, particularly where the Lemberg test (and some others) for calcite can be effected. And, in the case of some igneous, metamorphic, or granitized rocks one may find it valuable to preferentially stain one mineral green and another yellow, then obtain a peel which accurately shows these contrasting colors.

Some workers prefer not to prepare a cellulose mixture, but to merely pour or paint acetone on cellulose sheets and then apply the sawed, lapped, or polished rock (that has also been etched in acid) to this wetted surface. Others have prepared the cellulose mixture containing ingredients much as indicated in this paper (except that it is thicker and more viscous) to use in the field. Such procedure can be successfully carried out, particularly where one passes relatively flat-lying rocks, applies the mixture, then returns later in the day to remove the peel. The writer has discovered that certain outcrops can be so treated, and much larger than normal peels obtained. In this way larger-scale fabric and structure can be obtained. Successful attempts at obtaining stained peels were made in the field in numerous areas in Utah and Nevada. If the field geologist keeps stock solutions of cellulose material, and certain chemicals, in his vehicle he invariably will find use of them.

The writer has noted that it is a common problem among geologists to find storage space for the hundreds and thousands of samples and specimens collected in the field. Invariably these rocks, whether slabbed or not, are stacked in numerous areas such as on desks and tables, and piled in trays and drawers. Obviously there are difficulties in haphazard storage practices. Whether or not all or any of these rocks are stained may not be as important to the collector as having cellulose peels of the sawed and/or lapped surfaces for microscopic study, projection, and scientific filing. If the rock contains minerals which are susceptible to stains, for example, potash feldspars—yellow; nepheline—green; calcite—red-brown, or blue, or black, etc. (see Fairbanks, 1925, pp. 126–27; Gabriel and Cox, 1929, pp. 290–92; Keith, 1939, pp. 561–65; Shand, 1939, pp. 508–13), and these stains can be picked up accurately by a cellulose peel, the worker should avail himself of this asset because of the ease of examination, mineral counting, measuring grain and crystal size, and the eventual storing of the facsimile of his specimen. The writer has found that the peel is of itself an excellent negative for contact prints, and also for using as a negative to prepare enlargements and lantern-slides. Furthermore, the advantage of using a

stained peel (or even peel without stain) mounted between 2″×2″ or lantern-slide glasses for projection in teaching, meetings, etc. is readily realized. The writer would not suggest that the stained peel is a substitute for actual specimens, but it can prove a valuable supplementary and complementary phase of field and laboratory investigations.

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FIGS. 1–6, DECEMBER, 1957

MECHANICAL CONSTITUTION OF CERTAIN PRESENT-DAY EGYPTIAN DUNE SANDS[1]

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ABSTRACT

A purely graphical and descriptive study is carried out of the results of the mechanical analysis of aeolian sand samples from five aeolian microenvironments of the Suez Canal Zone. These microenvironments are shown to differ by small but significant amounts. Taking into account the geographical environment, the results are found to agree with a deduction from Bagnold's Theory of Saltation, allowing for the effects of grain size variation of the materials taking part in the process.

INTRODUCTION

Sixty years ago, Udden applied mechanical analysis to the study of sedimentary rocks (Udden, 1898). He divided aeolian deposits into their depositional forms, but paid comparatively little attention to the nature of the parent material. In a later paper dealing with all kinds of clastic sediments, he showed that widely differing deposits such as glacial till and beach sand were easily distinguishable, but claimed that similar deposits such as beach and dune sand were inseparable (Udden, 1914). New and more complex statistical methods have been introduced, but with little success in separating sands of similar grain sizes. Twenhofel (1941, p. 54) stated that one cannot identify the environment and agents of deposition from graphs and histograms, but can only suggest a possible environment and agent of deposition, since sediments deposited in different environments yield identical graphs.

This view appears to have been widely accepted; at any rate, it does not appear to have been seriously challenged in the last fifteen years.

During part of his Military Service, the writer was working on road and airfield construction in the Suez Canal Zone and had a soil laboratory at his disposal. While carrying out mechanical analyses, it was noted that the mechanical composition of dune sand seemed to be remarkably constant. In his spare time, a study was made of these sands in the area, sampling as many different kinds of deposits as possible.

[1] Manuscript received September, 1956.

METHODS USED

Field Sampling

Samples were always collected from single layers, care being taken to avoid inaccuracies due to the amount sampled. Owing to Service conditions in the Suez Canal Zone, it was not always possible to collect exactly where and as often as one would have liked.

Laboratory Examination[2]

British Standard 8″ sieves were employed, the number and size of the sieves being chosen according to the accuracy required in each range of gradings. In this way, the shape of the curve was determined to a considerable degree of accuracy. The sieve apertures used are shown in table 1. They have been checked with a travelling microscope.

Each fraction in each sample was sieved to about the same degree of accuracy, in spite of the small size and large number of sieves involved, as well as the variations in quantities from sample to sample (Wentworth, 1927). By using the whole sample, inaccuracies due to splitting were avoided. Accuracy of weighing the fractions was altered according to the overall accuracy of the method.

Initial Representation of the Basic Results

Existing methods are of two kinds: tabular methods and pictorial methods. The latter are easier to understand but the former must also be given since interpolation of the data from a pictorial method necessarily results in inaccuracies.

[2] Further details will be found in the thesis for the degree of M.Sc., deposited in the University of London Library (Harris, 1955).

The original tabular method of Udden, (1898), is used here as it is an ideal, if somewhat long form, the accuracy being that of the field and laboratory methods. It also makes it possible to compare results from different sieves by any chosen method without any extra interpolation or calculation.

The pictorial method chosen is that using cumulative curves based on the phi scale as proposed by Krumbein, (1936). It is now generally accepted as the best of the scales so far suggested owing to its ease in subsequent description and interpolation. By showing the exact values on the graph, the accuracy of the curves can readily be seen, while it gives a very satisfactory quantitative picture regardless of the actual sieve sizes used.

Specific Methods of Study of the Results

These are methods applied to the various fundamental features of the resultant curves so as to study their causes, breaking the latter down into single factors as far as possible.

The main critical features requiring care ful study in the cases presented in this paper are:

1.—Minimum and maximum grain sizes.

2.—The degree of similarity (both quantitative and qualitative) between samples from a common source, e.g., normal aeolian desert sand.

Similarity of maximum and minimum grain sizes may be expected to occur in aeolian sands (Bagnold, 1941, p. 98). To find the actual value involves interpolation or extrapolation from the cumulative curve. The close spacing of the sieves used in the pres-

TABLE 1.—*The sieve apertures used in this paper*

B.S. Sieve No.	Sieve apertures (mm) used for samples	
	1–71	72 and above
3″	76.2	—
1½″	38.1	—
¾″	19.05	—
⅜″	9.5	9.5
3/16″	4.8	4.8
7	2.35	1.92
14	1.17	0.96
18	—	0.73
25	0.592	0.60
36	—	0.56
40	0.402	—
52	0.318	0.38
60	0.261	0.25
80	0.191	—
85	—	0.18
100	0.144	0.17
150	—	0.10
200	0.073	0.076
300	—	0.053

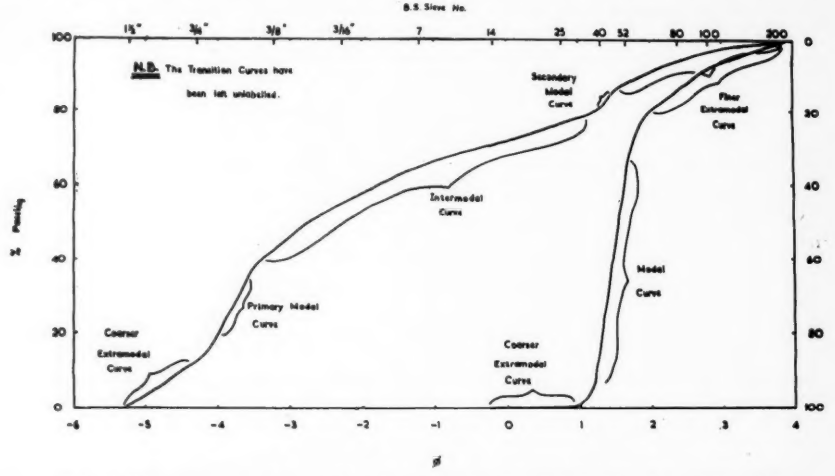
B.S. Sieve No.
1½" 3/8" 3/8" 3/16" 7 14 25 40 52 80 100 300
N.B. The Transition Curves have been left unlabelled.
Secondary Modal Curve
Finer Extremodal Curve
Intermodal Curve
Modal Curve
Primary Modal Curve
Coarser Extremodal Curve
Coarser Extremodal Curve
% Passing
100 80 60 40 20 0
0 20 40 60 80 100
-6 -5 -4 -3 -2 -1 0 1 2 3 4
φ

FIG. 1.—Nomenclature of the parts of the cumulative curve for unimodal and bimodal deposits applied to samples 4 and 34 (dune sand and wadi gravel respectively).

ent study gave fairly reliable results.

It is difficult to discuss collectively the characteristic components of a group of related curves unless the parts are given names.

The term "mode" has already been applied to the highest point reached on a size frequency diagram, and this should not be used in any other sense.

The prefix "primary," "secondary," "tertiary," etc., as applied to the maxima according to order of importance can still be used. Where steep parts of the curve occur, corresponding to modes, these will be called the "modal curves." These may vary in unimodal sediments from the steepest part of a continuous curve, e.g., deltaic type sediments, to a long steep straight part as in dune sands. Where there are two or more modes present, the steep parts are usually of the same character and can fairly easily be separated from the transition curves to the normal curve between the modes, i.e., the "intermodal curve." The parts of the curve between the nearest mode and either the maximum or minimum grain sizes will be called the "coarser" and "finer extramodal curves" respectively. This terminology has been applied to a sample of wadi gravel (37) and one of dune sand (4) in figure 1.

The equivalent grade of Baker (1920, p. 366–370), is the most convenient for study of the quantitative aspect of variation between related samples. The logarithmic equivalent grade or geometric mean diameter (Krumbein and Pettijohn, 1938, p. 256), determined on the phi scale of the cumulative curve is used here. The resulting value is coarser than the equivalent grade since the scale is shortened progressively with the coarseness of the grade. The median is not specific, except for parallel curves, since a change in shape may or may not result in a change of median.

GEOGRAPHICAL SETTING

The area studied is located in the Suez Canal Zone on the west side of the Canal and the Gulf of Suez (fig. 2). It stretches from the undulating hills north of Moascar and Ismailia to the plain occupied by the combined mouths of the Wadis Ghweibba, Bad, and Hagul, north of 'Ain Sukhna. Figure 2 also shows the limits of superficial deposits in the area (after Hume, 1925), and the main geographical districts.

Climatological data will be found in the Climatological Norms for Egypt (Ministry of War and Marine, Egypt, 1950), and in two papers by Sutton (1947, 1950).

The published data for the dominant and prevailing wind directions is shown in figure 2. However, considerable local modifications occur in the more hilly districts and coastal areas, apart from the relatively minor variations of speed with height, noted by Carroll (1939). Winds generally tend to follow the course of valleys and wadis where they are deep enough for the sides to deflect the wind. Along a coast, land and sea breezes frequently occur owing to the lack of vegetation cover and the clear sky. An extremely important local wind is the onshore (east) wind at 'Ain Sukhna, which blows regularly between 1200 and 1600 hours during the summer. It is strongest just south of Bir Themada, but dies out quickly inland, the limit of range of its effective transporting power being about 2–2½ miles. Other winds are non-turbulent when strong enough to move sand grains, whereas this wind frequently changes from a series of sand-devils (locally called "gibli"—singular), to dust-storms and vice versa, as one watches. The waves or centres of turbulence are about ¼–1 mile apart, separated by quieter conditions.

AEOLIAN SANDS—GENERAL

The results of the mechanical analysis of the samples of aeolian sand from various kinds of deposits collected throughout the Zone are given in tables 2–7, together with sample 27, whose origin will be discussed below. Figure 2 shows the location of the samples.

All types of sand were sampled, including those deposited around artificial obstacles. The samples were collected over a period of two and a half years. During the first year (June 1953–4), several khamsins occurred, with very strong south-west winds, but during the second year (June 1954–5), no really strong winds affected the area. Thus the samples might be expected to show the maximum possible variation for the conditions prevailing in the area.

As will readily be seen, certain characteristics hold:

1.—The minimum grain size lies within a very small range in all samples, with a range

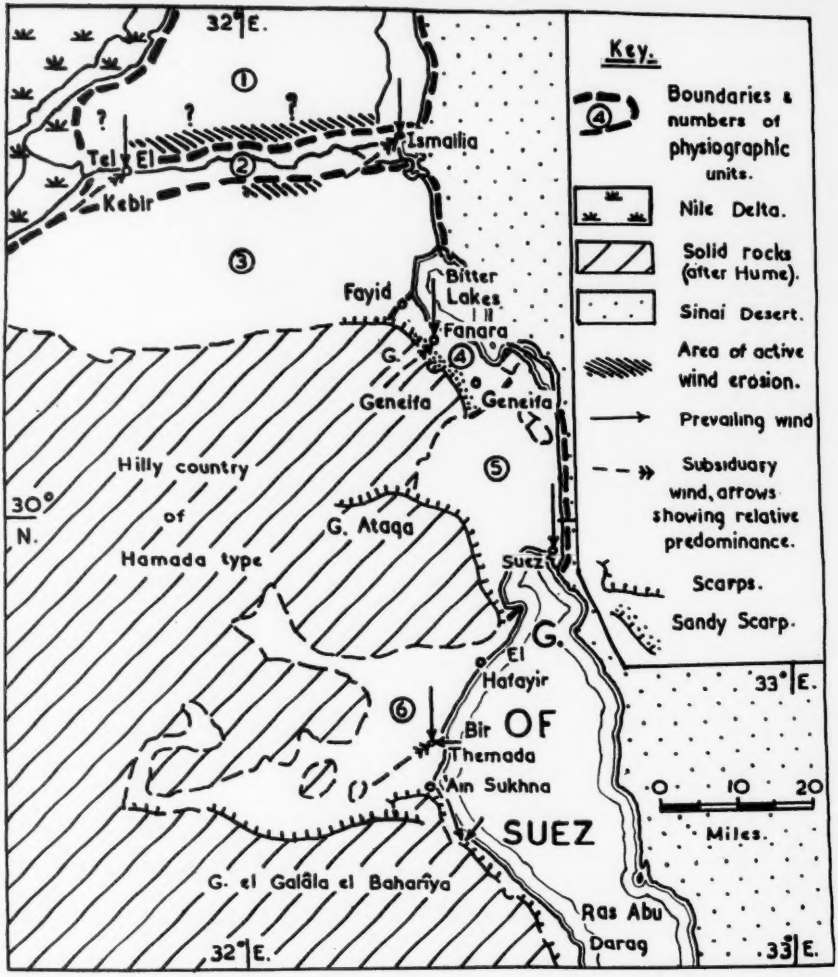

FIG. 2.—Map of the Southern Suez Canal Zone showing the winds (mainly after Met. Norms, 1950), the limits of solid geology (after Hume, 1925), the physiographic units, and main sampling sites.

from 0.05 to 0.08 mm.

2.—Apart from samples 9 and 10, there is always a marked amount of material in a wide range of finer extramodal grades.

3.—Except for samples 12, 14, 76, 78–9, 84 and 16, the maximum grain size lies between 0.45 and 1.20 mm.

4.—With the exception of samples 12, 76, 78–9, and 84, there is a marked lack of coarser extramodal curves.

5.—The range of medians, numbers 9, 10, 14 and 16 excepted (i.e., all those of normal desert deposits), lies between 0.20 to 0.42 mm, or 2.36 to 1.28ϕ.

6.—The range of log. E.G., numbers 10, 14, 80–3, and 16 excepted, lies between 1.92 and 1.47ϕ.

The first characteristic is consistent with Bagnold's Theory of Saltation (1941, p. 98). The reasons for the other characteris-

TABLE 2.—*Mechanical analyses of samples showing the stages in the wind erosion of deltaic sands from the Nile Delta area*

Sample No.	% Passing B.S. Sieve No.										Grain Size (ϕ)			
	⅜″	⅛″	7	14	25	40	52	80	100	200	Min.	Max.	Median	Log. E.G.
5	—	—	—	100	99.6	85.7	38.9	12.9	6.5	0.3	3.90	−0.23	1.55	1.74
12	—	100	99.9	98.8	94.5	58.2	26.0	12.3	8.1	1.2	4.00	−2.29	1.35	1.51
13	—	—	—	100	94.0	48.6	25.6	11.2	8.5	1.3	4.30	−0.23	1.28	1.49
17	100	98.3	93.4	85.5	75.7	58.5	39.3	21.1	13.6	2.4	4.05	−3.23	1.42	1.35
18	100	98.2	94.8	90.6	86.3	73.5	54.0	34.4	21.5	4.0	4.05	−3.23	1.75	1.75
19	100	96.4	91.9	81.8	65.1	51.9	37.0	14.1	9.1	1.5	4.25	−3.23	1.37	1.06
20	—	100	95.4	87.6	74.5	n.d.	38.7	n.d.	13.7	2.8	4.35	−2.29	1.40	1.35
21	—	100	98.8	96.7	92.3	n.d.	42.6	n.d.	10.9	1.1	4.05	−2.29	1.53	1.655
22	—	100	99.1	96.4	89.4	n.d.	41.7	n.d.	12.9	1.1	3.95	−2.29	1.50	1.595
23	—	100	96.6	94.3	89.8	n.d.	38.9	n.d.	9.9	1.0	3.90	−2.29	1.50	1.57
24	—	100	99.4	98.5	94.8	n.d.	49.1	n.d.	11.3	0.7	4.05	−2.29	1.63	1.725
25	100	99.2	97.3	93.2	86.2	n.d.	39.3	n.d.	10.5	1.1	4.00	−2.90	1.47	1.495
26	—	100	98.6	96.2	90.8	n.d.	42.3	n.d.	8.9	0.8	3.95	−2.29	1.53	1.60

Sample 5 —From drift sand in the lee (south) of a plant, G.R. 7335, 8755.
Sample 12 —From a whaleback mound on eroded deltaic sand, G.R. 7337, 8754½.
Sample 13 —From a whaleback mound on eroded deltaic sand, G.R. 7312, 8777.
Sample 17 —Typical sample of undisturbed deltaic sand from 20″ deep, G.R. 7312, 8777.
Sample 18 —Typical deltaic sand, 0–20″ deep, G.R. 7312, 8777.
Sample 19 —Typical clean deltaic sand, 1′–1′6″ deep, G.R. 73373, 87545.
Sample 20 —Wind disturbed deltaic sand, G.R. 7337, 8738.
Sample 21–26—Samples of blown sand in the form of low whaleback dunes or sand heaps, 0–3″ deep, G.R. 7337, 8754.

tics, as well as the exceptions, will be discussed below. At the same time, it is worth while noting that the first two characteristics apply to all these samples, in spite of the specialised modes of occurrence, i.e., they are primary characteristics.

DETAILED STUDY OF THE AEOLIAN MICROENVIRONMENTS

In order to consider the samples in detail, it is first necessary to separate the different petrogenetic provinces or aeolian microenvironments present in the area. These are:

a.—The area of active erosion of the Pliocene deltaic sands, found in area 1, and forming a narrow discontinuous belt along the north edge of area 3. In these areas, sands showing all the stages from true deltaic sands to true dune sands occur. Also included in this group is the Tel El Kebir-Ismailia depression (area 2), into which the sand is encroaching from the areas of erosion to the north and south.

b.—Area 3, south of the Tel El Kebir-Ismailia belt of erosion, stretching for 20 miles towards Fayid. The sand is derived from the northwest, and the over-all grain size progressively decreases southwards.

c.—The blown sand occurring in the form of local pockets (as at El Hafayir), and as piles around plants on the coalesced wadi fans south of Fayid in areas 4, 5, and 6. Owing to Active Service conditions, it was only possible to sample in areas 4 and 5. The exact origin of the material in area 6 is uncertain, but it probably comes from the Nile Valley. In the extreme north of area 4, it comes from the edge of the Delta where erosion is occurring, as noted above.

d.—The Sandy Scarp deposits along the northeast facing scarp of the Tertiary limestone hills of area 4.

e.—The Bir Themada-'Ain Sukhna pocket of blown sand in area 6.

With the possible exception of the last case, all the microenvironments initially include available material of range 0–4ϕ.

Wind Erosion of the Deltaic Sands of the Nile Delta Area

Owing to the sporadic outcrops of deltaic and dune sands, each depositional type was sampled in the hope that by taking enough samples, a good idea of the change in grading from undisturbed deltaic sand to dune sand would be obtained.

The exact locations and results of mechanical analyses of the samples are given in tables 2 and 3. As will readily be seen, these fall into three main groups:

1.—Samples 17, 18 and 19,—typical deltaic sand. These undisturbed sands are quite distinct, having a wider range of grading, while there is no marked modal curve. The logarithmic E.G.'s are coarser, too, ranging from 1.06 to 1.75 ϕ.

2.—Samples 5, 72–77. Apart from sample 76, these fit in with the characteristics of the aeolian sands noted above. Sample 76 has a larger coarser extramodal curve and conse-

TABLE 3.—*Mechanical analyses of samples showing the stages in the wind erosion of deltaic sands from the Nile Delta area*

Sample No.	% Passing B.S. Sieve No.												Grain Size (φ)			
	$\frac{3}{8}$"	$\frac{3}{16}$"	7	14	18	25	36	52	60	85	100	150	200	300	Min.	Max.	Median.	Log. E.G.
76	100	99.8	99.6	99.4	98.7	97.2	95.4	79.5	43.2	15.8	11.4	3.0	0.9	0.2	4.30	−3.23	1.88	1.92
77	—	—	100	99.9	99.2	97.3	93.9	48.6	11.6	4.7	3.6	1.0	0.2	0.0	4.00	−0.93	1.48	1.53
78	100	99.9	99.8	98.7	95.6	90.5	85.6	58.0	24.9	8.8	6.5	1.7	0.5	0.1	4.30	−3.23	1.50	1.515
79	—	100	99.7	99.7	93.4	86.8	81.4	56.3	24.2	11.0	7.9	2.2	0.7	0.2	4.30	−2.29	1.52	1.585

Sample 76—From a pile round a desert plant half way between Tel El Kebir and El Qassasin on the desert road.
Sample 77—From a pile round a barbed wire entanglement, G.R. 7306, 8771.
Sample 78—From a pile at the base of a cable pylon, El Qassasin Swimming Pool.
Sample 79—Sand piled round a desert plant, 1¼ miles east of Tel El Kebir Garrison main gate on the desert road.

quently a coarser maximum grain size.

3.—Samples 12, 13, 20–26, 78 and 79. These form a complete transition between these two end members.

It seems reasonable to deduce from Bagnold's work (1941, p. 102), that the grades available for transport at any one time and place will consist not only of the wind-borne grades entering the area, but also the grades of suitable size already present and available for transport in the area. The abnormal character of sample 76 may therefore be explained as due to mixing of either deltaic or intermediate sand with a coarser extramodal curve, and typical dune sand.

The samples 19–26, 12, and 5, from the Moascar-Nefisha area can be taken as representative, covering the complete sequence from deltaic to normal aeolian sands. In the case of samples 21–26, which were collected under similar conditions very close together, sample 22 seems to be the average curve, so it will be taken as typical. This sample, together with the other four from the same area have been plotted in the form of cumulative curves in figure 3 and show the following stages:

1.—The immediate reduction in maximum grain size and increase in minimum grain size, with consequent apparent increase in the finer extramodal curve.

2.—Reduction in the excessive coarser constituents continues until complete. As the last of these grades is removed (sample 12), there is a reduction in the quantities present in the finest grades, bringing the curve more nearly to that of a normal aeolian sand, e.g, sample 5.

3.—Finally, there is a lateral shift of the modal part of the aeolian sand curve (see samples 12 and 5), indicating a gradual reduction in total grain size of the sample to a form in complete equilibrium with its process of transport and deposition.

Similar results are found with the samples from other areas.

A possible way of accounting for the shape of the curve for aeolian deposits may be obtained by considering in greater detail what happens during saltation.

Since the grains involved are of various sizes, a larger grain landing may knock either one or two larger grains into the air, or several small grains, as it comes to rest.

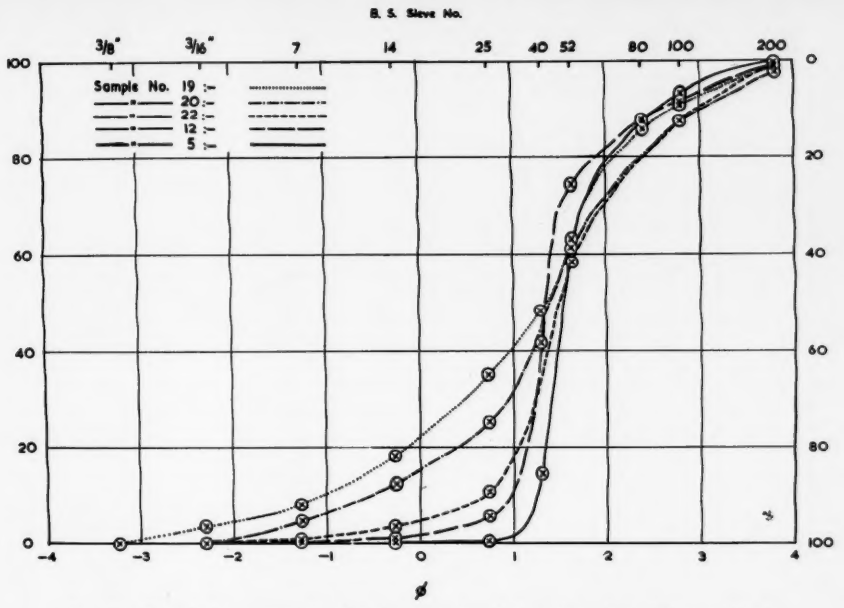

FIG. 3.—Cumulative curves showing the stages in wind erosion of the Pliocene deltaic sands of the Moascar-Nefisha district, Suez Canal Zone.

However, in the case of a small grain landing, it will only disturb a large grain if the latter is hit favourably when in a most unstable position, otherwise, it will bounce instead, as it does on a hard rock surface. Nevertheless, it might be expected to suitably disturb a grain of its own size. Thus, there would be a tendency for fewer coarse grains to be carried during saltation than fine grains. This would result in a slow but sure reduction of the finer grains while the coarser grains would gradually be left behind. This process would continue until a condition is reached at which there are just enough small grains to fill the interstices between the coarser grains. The latter must then be removed before the finer grains become liable to the action of saltation. We might therefore expect an ideal cumulative curve (the characteristic curve), representing the distribution of grain size in a deposit that will be in perfect equilibrium under the saltation process. All processes of erosion and transport would be expected to show a tendency to bring the composition as near to this theoretical composition as possible.

Should the material being transported become disseminated over a surface with different grades present, so producing a different total grading of the available material, this sorting process will tend to restore the composition of the grades transported to that of the characteristic curve. Thus, if this theory is correct, owing to the difficulty of the variations in available material and conditions of deposition, there will always be a slight variation of grading on either side of a characteristic curve for normal dune material at a particular time in a given area. This variation will be in a given direction for any particular environment, e.g., excess coarse material on the surface of coalesced wadi fans containing an abundance of the coarser grades.

On the other hand, the sand grains will tend to be reduced in size as they are blown to and fro. In addition, weak winds would be expected to move only the smaller grades. This would result in a gradual diminution in maximum grain size in the direction of the

TABLE 4.—*Mechanical analyses of the deposits of blown sand from area 3, Suez Canal Zone*

Sample No.	% Passing B.S. Sieve No.													Grain Size (φ)				Distance South of the Latitude of Nefisha Bridge (Miles)
	14	18	25	36	40	52	60	80	85	100	150	200	300	Min.	Max.	Median	Log. E.G.	
6	100	—	99.5	—	78.8	38.1	—	15.1	—	7.9	—	0.9	—	3.90	−0.23	1.50	1.77	1.00
11	—	—	100	—	98.8	48.3	—	13.8	—	4.9	—	0.0	—	3.60	0.75	1.63	1.82	2.34
80	100	99.9	99.7	99.2	—	89.1	47.0	—	17.8	12.1	1.4	0.1	0.0	3.80	0.08	1.95	2.20	5.00
81	100	99.8	99.4	99.0	—	96.0	78.8	—	36.1	24.7	3.6	0.4	0.0	3.90	0.08	2.35	2.36	17.0
82	100	99.6	98.2	96.3	—	77.5	49.0	—	22.4	15.3	2.5	0.4	0.1	4.35	0.08	1.97	1.97	7.25
83	100	99.9	99.2	98.1	—	86.8	54.7	—	29.9	23.6	6.9	1.4	0.1	4.30	0.08	2.08	2.15	8.00

Sample 6—From the crest of a seif dune, G.R. 7379, 8727.
Sample 11—From the windward base (west) of a 40′ high seif dune, G.R. 7404, 8701.
Sample 80—From the surface of an open dune, G.R. 7341, 5658.
Sample 81—From blown sand filling a shallow trench, G.R. 7375, 8472.
Sample 82—From sand piled round a plant, G.R. 7448, 8578½.
Sample 83—From dune sand piled against a rush matting fence, G.R. 7413, 8556.

TABLE 5.—*Mechanical analyses of the deposits of blown sand from areas 4 and 6, Suez Canal Zone*

Sample No.	% Passing B.S. Sieve No.																Grain Size (φ)			
	⅜″	⅛″	7	14	18	25	36	40	52	60	80	85	100	150	200	300	Min.	Max.	Median.	Log. E.G.
3	—	—	100	99.9	—	98.6	—	86.0	55.6	—	24.1	—	13.7	—	1.2	—	3.95	−1.23	1.74	1.96
4	—	—	—	100	—	99.8	—	80.2	37.2	—	13.6	—	8.8	—	0.6	—	3.90	−0.23	1.47	1.72
7	—	—	—	100	—	98.6	—	—	25.7	—	—	—	6.0	—	0.3	—	3.90	−0.23	1.42	1.61
8	—	—	—	100	—	95.8	—	—	26.8	—	—	—	3.3	—	0.0	—	3.80	−0.23	1.35	1.48
84	100	99.9	99.85	99.4	97.2	91.7	85.7	—	56.0	26.8	—	11.7	8.4	1.8	0.5	0.15	4.35	−3.25	1.52	1.62

Sample 3 —From a dune in gravel workings, G.R. 7494, 8383.
Sample 4 —From a heap in the lee (east) of a small ridge, G.R. 7521, 8305½.
Sample 7 —From drift sand around a plant, G.R. 7513, 7544.
Sample 8 —From a sand sheet, G.R. 7381, 8450.
Sample 84—Blown sand against a concrete slab, G.R. 7534, 8305.

prevailing wind, outward from the source of the material, provided no more coarser material was present in the area. Thus a gradual reduction in grain size of the coarser grades suitable for wind transport by saltation will, theoretically, tend to occur in an area where no suitable material is already available.

The Aeolian Deposits of the Nefisha-Fayid Area

Blown sand moves northeast and southeast from the belt of wind erosion just south of the Nefisha-Tel el Kebir depression (fig. 2). The sand blown northwards has not been sampled in this survey, due to its inaccessibility during the period of the writer's Service. That blown southwards has been sporadically sampled at several places along both the Treaty and Suez Canal Roads.

The physical environment has already been described. It is particularly interesting owing to the lack of further supplementary supplies of suitable grades for aeolian transport.

Thus, this area is considered separately from that to the south, where the wadi gravels on which the blown sand lies contain abundant available coarse grades.

The results for the samples collected in this more northerly area are shown in table 4, together with the distance due south of the latitude of Nefisha Bridge. There appears to be no marked change in the winds across the area (as far as records at Fayid and Ismailia indicate), and so distance south of the area of erosion should be a fair index of relative distance travelled by the blown sand.

The samples conform to the characteristics of the aeolian sands from the Suez Canal Zone, noted above, except that samples 80 to 83 are finer than usual (i.e., logarithmic E.G. less than 1.92ϕ). This would be expected in the area if reduction in grain size with distance is occurring.

Figure 4 shows the result of plotting the respective values of logarithmic E.G. against distance. A definite decrease in over-all grain size with distance south of Nefisha Bridge occurs (fig. 4), although there are too few samples for the exact trend of the curve to be shown with any great certainty.

The field covered by the cumulative curves is shown, together with those for the samples from the other provinces in figure 5, field D. It overlaps the field for the true dune sands of the area of wind erosion (field A) described above, and it is wider, extending much further towards the finer end of the cumulative curve. Thus these samples would appear to fit in satisfactorily with the characteristics noted above.

Aeolian Deposits on the Surface of the Coalesced Wadi Fans

These stretch eastwards from the Tertiary hills between Fayid and Bir Odeib. Addi-

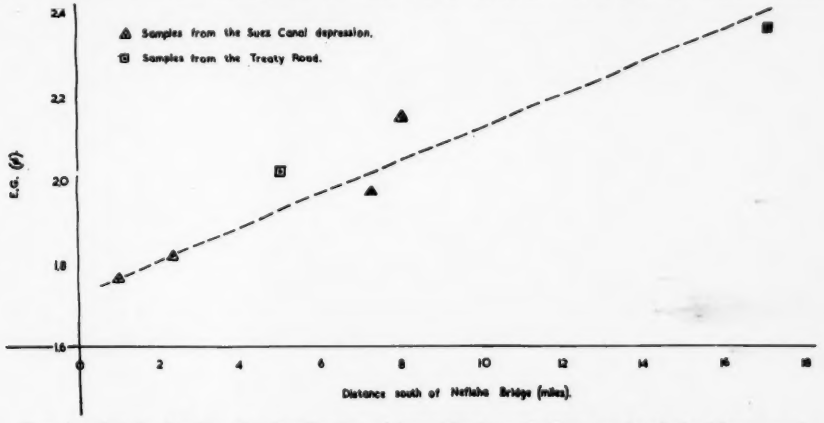

FIG. 4.—Graph showing the distribution of logarithmic equivalent grade of the blown sand samples from Area 3 in relation to distance south of Nefisha Bridge, Suez Canal Zone.

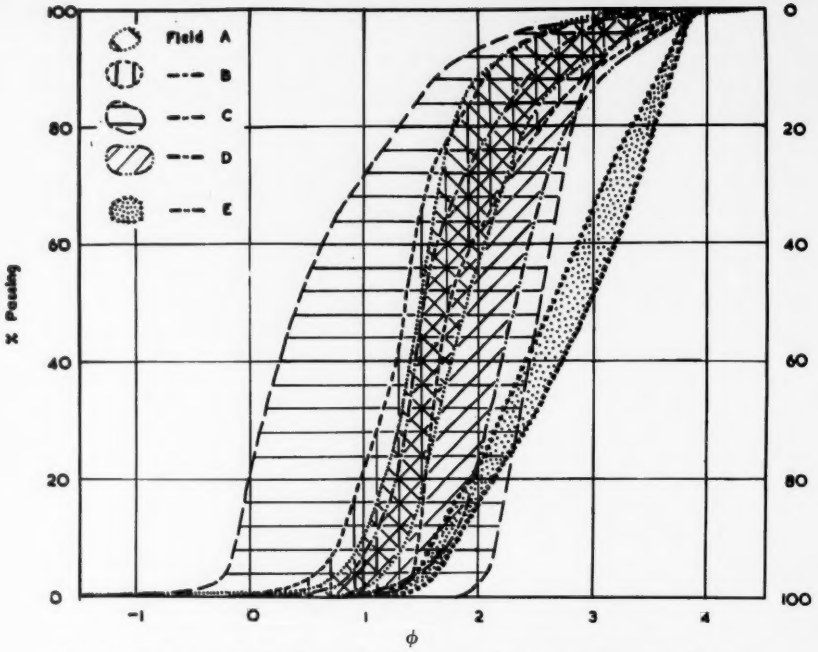

FIG. 5.—Fields occupied by the cumulative curves of the samples from the five dune sand microenvironments of the Suez Canal Zone.

tional coarser and finer grades are available on the surface of the fans and might be expected to have a noticeable effect on the grading of the sand.

The results for the mechanical analysis of the samples from this area are given in table 5. The samples conform to the characteristics of the aeolian sands of the area, noted above, apart from sample 84. This sample has an unusually coarse maximum grain size, and a coarser extramodal curve, which is not surprising in view of the excess coarser grades available.

Field B, figure 5, shows the field of the cumulative curves. The range is coarser than that for the area of wind erosion, while a greater percentage occurs in the finer extramodal curve.

Thus these results conform to the general pattern.

The Deposits of the Sandy Scarp, Geneifa

A covering of blown sand occurs along the face of the northwest-southeast escarpment bounding the Tertiary hills, west of the Treaty Road, south of Fayid.

Field relations show that the sand originates in part at least from the southwest, but the absence of tongue formations of the type described by Bagnold (1941, p. 192–193), suggest subsequent removal of the sand from the outwash fans and redeposition against the scarp by the prevailing north winds. These weaker winds are deflected along the surface of the scarp.

The sandy slope can be divided into two parts:

1.—The steep slope resting against the scarp and of fairly uniform slope. Northwest to southeast dunes or piles of sand are found behind obstructions on its surface, e.g., behind plants. These lie approximately parallel to the contours, while rippling is at right angles to this direction, i.e., the surface winds flow along the contours during sand movement.

2.—The gentler slope which forms a gradation from the steep pile to the actual wadi

courses which breach the lower ridge.

Considerable variation in grain size occurs in this sand. At the base, it is exceptionally coarse, being almost entirely composed of quartz grains coarser than 0.5 mm, but grades upwards until almost exclusively finer than 0.25 mm grain diameter near the top. In order to determine the nature and

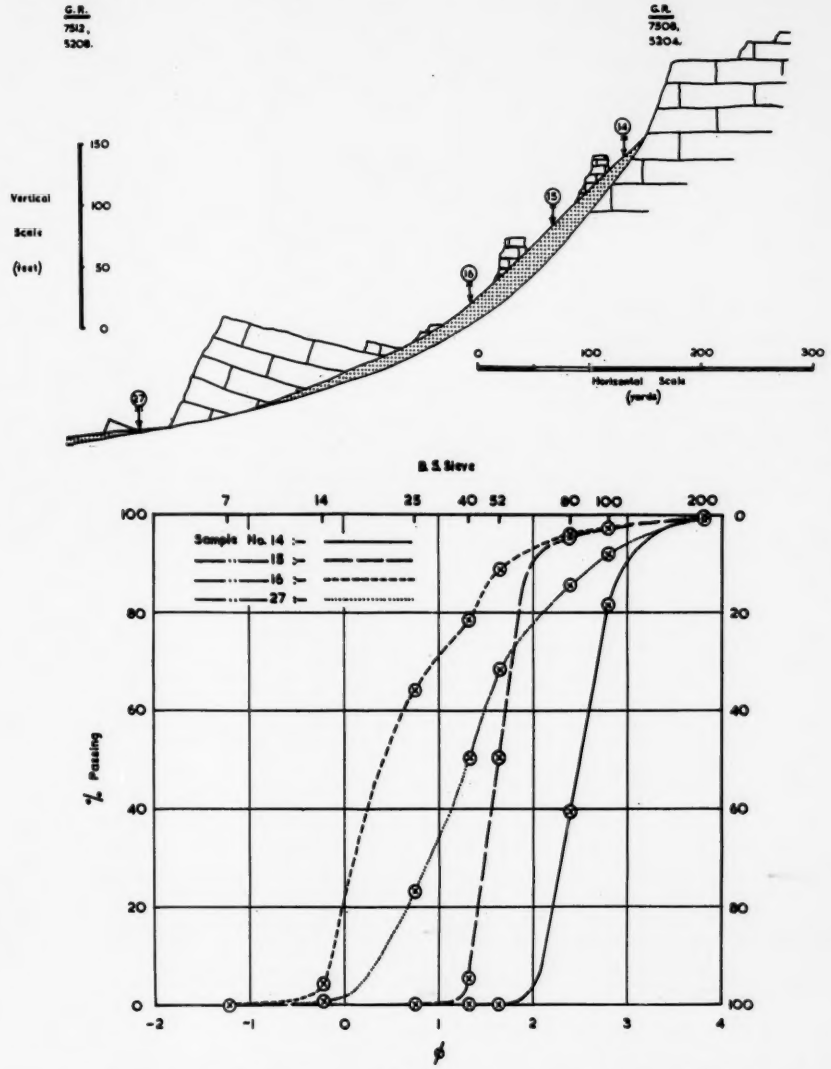

FIG. 6.—Position and cumulative curves of the samples from the Sandy Scarp, Geneifa, Suez Canal Zone.

The lower ridge exhibits inward dips due to either folding or faulting, but not due to rotational land-slipping.

TABLE 6.—*Mechanical analyses of the samples from the Sandy Scarp, Geneifa, Suez Canal Zone*

Sample No.	% Passing B.S. Sieve No.								Grain Size (ϕ)			
	7	14	25	40	52	80	100	200	Min.	Max.	Median	Log. E.G.
14	—	—	—	100	99.9	60.5	18.4	0.2	3.85	1.60	2.50	2.52
15	—	—	100	94.9	48.4	4.7	2.8	0.1	3.85	0.75	1.63	1.685
16	100	95.7	35.8	21.3	11.1	3.8	2.6	0.3	3.925	−1.23	0.42	0.675
27	100	99.3	76.9	49.4	31.9	14.3	8.0	0.8	4.10	−1.23	1.32	1.425

For locations of samples, see figure 6.

possible origin of this sandy deposit, a careful examination was carried out at Geneifa and four representative samples collected along a profile (fig. 6).

The mechanical analyses are given in table 5, while the cumulative curves will be found in figure 6. Apart from sample 15, the samples do not fit in with the characteristics noted above, since the field of the cumulative curves for samples 14–16 is exceptionally wide (see field C, fig. 5).

Sample 14 was taken from near the crest of the sand slope, about 100 feet up, while for contrast, sample 15 was collected from near the base of the main slope. The cumulative curves are essentially parallel with the same minimum grain size, (0.07 mm, fig. 6). However, the maximum grain size varies from 0.59 to 0.34 mm. Both are typical aeolian curves, and there is a lateral shift of the modal part of the curve. Thus both samples would appear to be formed under similar, typical, aeolian conditions, subject only to a variation of maximum grain size with height.

Sample 16 was taken from the extreme base of the scarp, and represents the culmination of the coarsening process. It is quite well graded, and obviously its composition is primarily aeolian controlled. It still contains only a small proportion of material outside the modal part of the curve, yet its minimum grain size is still 0.07 mm. It is, however, not quite as well graded as the usual aeolian sand, while a kink occurs at approximately 1.3ϕ.

Thus, samples 14–16 represent a successive reduction in maximum grain size, and therefore a reduction in wind velocity and transporting power with height (Bagnold, 1941, p. 138–139). The unusual coarseness of the total material must be due to an increase in the available grades just prior to and during transport to the scarp face. Thus it is probably due to the coarser grades available in the wadi outwash fan deposits to the northeast, since they are not present on the plateau to the southwest. Reduction in grain size of the material which is subject to surface creep at the foot of the slope is the probable cause of the accumulation of coarse grades there.

From this point onwards, the transition zone to wadi gravel is present with both aeolian and aqueous sorting involved, while the deposits are much thinner and limestone fragments appear in the sand. Just below the lower ridge, where the small wadi breaks through, occurs a much thicker deposit of sand, apparently corresponding to the "funnelling" deposit of Bagnold (1941, p. 191–192). Sample 27 was taken from here but is not nearly as well graded as the aeolian deposits. The minimum grain size is the same as for the other samples, but since the two sources of material are aeolian sand (both similar to sample 16, and that characteristic for normal dune deposits in the area), and limestone fragments, this is to be expected. Notice also the increase in finer grades and the wide range of grades covering a similar range to the entire aeolian deposit. This sample probably consists of a mixture of the characters of aeolian sand and water-lain sand (the former being dominant), and shows the first effects of the headwaters of the wadis, i.e., it is probably not a purely aeolian deposit. Further evidence on this matter will be given in a later paper.

Thus, these samples still appear to agree with deductions from the physical hypotheses put forward by Bagnold, the exceptional depositional histories offering an explanation of the peculiarities in grading.

TABLE 7.—*Mechanical analyses of the samples of dune and beach sand from Bir Themada, Suez Canal Zone*

Sample No.	% Passing B.S. Sieve No.										Grain Size (ϕ)			
	¼"	7	14	25	40	52	60	80	100	200	Min.	Max.	Median	Log. E.G.
9	—	—	—	100	99.8	94.9	n.d.	69.1	54.6	3.2	3.85	0.75	2.93	2.79
10	—	—	—	100	98.3	90.0	n.d.	69.6	42.8	2.5	3.85	0.75	2.72	2.685
51	100	99.9	99.3	96.5	88.5	37.5	13.1	n.d.	0.1	0.0	—	—	1.52	1.58
52	100	99.6	98.5	93.5	73.9	24.4	n.d.	n.d.	0.1	0.0	—	—	1.40	1.47
53	—	—	—	100	98.5	69.1	30.2	n.d.	0.5	0.0	—	—	1.78	1.83
54	—	—	—	—	100	82.1	22.6	n.d.	0.2	0.0	—	—	1.80	1.84

Sample 9 —From the base of the lee side of a west facing dune, G.R. 7453, 7727.
Sample 10—From the 12′ high crest of the same west facing dune, G.R. 7453, 7727.
Sample 51—From a point on the beach flat, 30 yards behind the present storm beach, G.R. 7465, 7743.
Sample 52—From 5′ below high water mark, G.R. 7465, 7743.
Sample 53—From 30 yards below the main beach, G.R. 7465, 7743.
Sample 54—From just above low water mark, G.R. 7465, 7743.

The Bir Themada-'Ain Sukhna Pocket of Blown Sand: A Study of a Closed System

All the areas described up to now have been areas into, across, and from which blown sand is transported, i.e., open systems.

The local easterly onshore wind in the Bir Themada-'Ain Sukhna area rapidly dies out inland while the predominant southwest wind blows for only a few days each year. The prevailing north wind is usually fairly weak and alternates with the much stronger east wind. To the south rises the fault scarp of the Gebel el Baharîya el Galâla. Thus the wind system is such as to confine the sands in the area to a pocket of limited size, i.e., it is a closed system.

The sources of the sand are two-fold:

1.—Derived from wind erosion of the intertidal and beach deposits by the strong east wind.

2.—Blown in from the southwest or north by winds blowing across the surrounding wadi gravel covered fans and hamada type hills.

Sand was observed to enter the area from the southwest during khamsin sandstorms, while the east wind always brings with it sand, including some from the 50-yard wide beach of accretion and intertidal flat. As Carroll (1939) has observed, the fact that intertidal sand may never dry out will not prevent wind erosion if the wind be stronger on average than about 20 mph. The material forming the intertidal zones and beach face (blown sand, reworked wadi gravel, and shells) must therefore be examined in any study of the aeolian sand. The material brought in from the southwest and north will correspond to the typical grading of aeolian sand resting on wadi gravel as described above, i.e., it will include the full possible range of grades normally found in aeolian deposits (4ϕ). We might expect to find a large scale mill in this pocket in which the sand is blown to and fro and gradually reduced in grain size.

The results of mechanical analysis of aeolian and beach sand samples from Bir Themada will be found in table 5. Comparison of the cumulative curves for two analyses of aeolian sand (samples 9 and 10), with two beach samples (samples 51 and 52), and two intertidal sand samples (samples 53 and 54), shows that the latter lack grades finer than 2.75ϕ, but contain a moderate amount of all the coarser grades up to 1ϕ. Thus the parent material must originally contain all the coarsest grades, although a slight deficiency in the finest grades (2.74–4.00ϕ), might be expected. However, the aeolian sand is extremely fine grained, only fairly well graded, and is bimodal. There is no finer extramodal curve discernible, while the coarser extramodal curve is extremely small. The slight secondary mode is consistent with the results of laboratory mill experiments, sample 9 representing one of the later stages in the process of abrasion (e.g., Marshall, 1929). The log. E.G., and median values are exceptionally fine, while the field occupied by the cumulative curves (see field E, fig. 5), agrees with such an origin.

CONCLUSIONS

A purely graphical and descriptive study was carried out of samples of dune sand from the Suez Canal Zone of known depositional environment. A number of microenvironments can be recognised. Whilst there are a

number of characteristics common to all these aeolian sands, slight differences can be recognised due to the microenvironment. An attempt has been made to explain these differences by a deduction from Bagnold's Theory of Saltation by considering the effects of the relative grain sizes of the particles taking part in the process.

ACKNOWLEDGEMENTS

This paper forms part of a thesis for the degree of Master of Science in the University of London. Thanks are due to the War Office for permission to publish the results of certain mechanical analyses carried out while on duty in the Suez Canal Zone. Dr. J. F. Kirkaldy has been a constant source of encouragement and patient and constructive criticism throughout the work. The photographic staff of Queen Mary College, London, helped with the illustrations.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 4, PP. 435–446
FIGS. 1–6, PLATE 1, DECEMBER, 1957

TRENDS OF SEDIMENTATION IN GIRIDIH BASIN, BIHAR, INDIA[1]

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ABSTRACT

A detailed lithologic and petrographic study of the sedimentaries of the Giridih Basin was under taken. The chief rock types belonging to the Lower Gondwana subdivision (Upper Carboniferous) are represented by two stages, Talchir and Karharbari.

The Talchir Stage consists of a boulder bed, needle shales, with alternating lenses of silty sandstones, and coarse grits. The boulder bed is unfossiliferous as are the silty sandstones and the coarse grits, but the needle shales frequently contain inclusions of carbonaceous material.

The Karharbari Stage starts with a conglomerate at the base and consists chiefly of alternating grey arkoses, micaceous shales, carbonaceous shales, and coal seams. The arkoses are cross bedded, the cross bedding being of the type that is usually characteristic of shallow water current.

All lines of evidence suggest that the Talchirs are in part glacial and in part glaciofluvial and that the lake basin became shallower at the close of the Talchir period. The Karharbari sediments were interpreted as having been deposited in shallow water and based on cross bedding and heavy mineral constitution were thought to have been derived from a proximate western source.

INTRODUCTION

The Giridih Basin (24°13′–24°14′N.; 86°15′–86°17′ E.) ranks as one of the most important of the Indian coal fields because of its excellent coking coal (figs. 1, 2). There are not many references to this coal field in the literature, although McClelland's (1848), was the first authentic description (quoted by Fox, 1934). Subsequent reports about this field can be found in the works of Oldham (1852), Wilson (1859) and Hughes (1870), as quoted by Fox (1934). The floral assemblage of the Karharbari strata are described in detail by Feistmantle (1875), while Saise (1894) correlated the various coal seams. A comprehensive summary of the Indian coal fields and the Gondwana System was given by Fox (1931, 1934).

Most of these accounts were presented with special significance to coal, and references to the lithological and petrological aspects of the rocks have been astonishingly few in the past. Sen and Raychowdhury (1948) and Sen (1949) published a few results of the mechanical composition and the shape studies of the Raniganj, Panchet and Supra-Panchet Stages. An attempt was made in this paper to present the gross lithological and petrological features of the Talchir and the Karharbari Stages of the Lower Gondwana subdivision and their history of sedimentation.

[1] Published by permission of the Director, Indian Institute of Technology, Kharagpur, West Bengal, India. Manuscript received October 15, 1956.

GEOLOGIC SETTING

The Lower Gondwana rocks of Giridih occupy an oval-shaped basin in the midst of gneisses, west and south of the town of Giridih. The basin, about 12 square miles in area, is bounded on the north and south by two east-west running boundary faults and is cut across in the middle by a third fault also running east-west (fig. 3). The following sequence represents the general order of rocks in order of their antiquity:

Artinskian	Lower Gondwanas	Karharbari Stage	Alternating arkoses, bluish grey and brown micaceous shales, carbonaceous shales, and coal seams
		Unconformity	Thin conglomerate horizon
Upper Carboniferous		Talchir Stage	*Fine to coarse grained, greenish sandstones*
			Bluish black shales with chert nodules
			Green,splintery shales
			Boulder conglomerate
		Unconformity	
			Metamorphics

METAMORPHICS

Giridih Basin is surrounded on all sides by metamorphic rocks, which consist of muscovite schists, quartzites and garnetiferous schists, and gneisses. They are cut across by quartz reefs and pegmatites which are exploited for their mica content.

TALCHIR STAGE

Lithology and Stratigraphy

The Talchir Stage in the Giridih Basin consists successively of basal boulder conglomerate, green splintery shales, bluish black shales with chert nodules, and fine to coarse sandstones. The rocks possess a uniform earthy green colour, changing at places along the strike into bluish black, more particularly seen in the needle shale horizon. The junction between the boulder bed and the overlying needle shales is quite conformable, stray boulders having been found embedded in the lower horizons of needle shales at the contact.

The boulder bed consits of pebbles having a large range in size. Eighty percent of them fall in the pebble size range of Wentworth. Pebbles are faceted and well rounded, but grooved and striated specimens indicative of actual glacial transport are rare. The composition of pebbles ranges from vein quartz to typical quartzites and thinly laminated garnetiferous gneisses and schists. The pebbles do not exhibit any marked preferred orientation. The groundmass is greenish and contains perhaps chlorite as one of the chief constituents. At places a conspicuous bedded character is discernble in the conglomerate which is generally horizontal, although a slight northerly dip of 4° has been noticed in the northern part of the basin. The conglomerate is unfossiliferous.

The needle shales overlying the conglomerate are greenish and break into sharp, angular fragments. They are interbedded with thin lenses of green silty sandstones. Both the shales and the sandstones are slightly calcareous.

Plant fossils are rare and are restricted to a few poorly preserved impressions of stems. Inclusions of carbonaceous matter are widespread throughout the shales. The impressions are found in the lower horizons of the needle shales a few feet above the boulder conglomerate. Fossils from the Talchir shales were described previously, but only from the uppermost layers, a few feet below the junction of the overlying Bara-

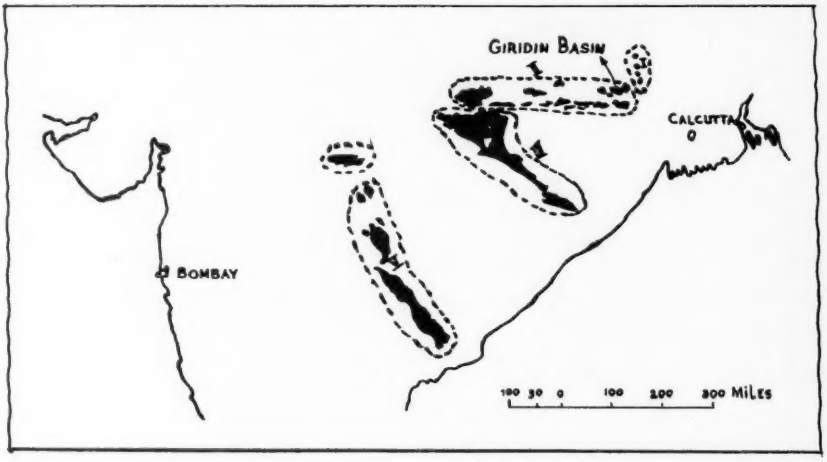

FIG. 1.—Lower Gondwana formations in the Deccan Shield.
I. Rajamahal Basin.
II. Deoghar, Karharbari, Jharia, Raniganj South, North Karanpura, and Giridih Basins.
III. Mahanadia and Chattisgargh Basins.
IV. Satpura Basin.
V. Godavari and Wardha Valley.

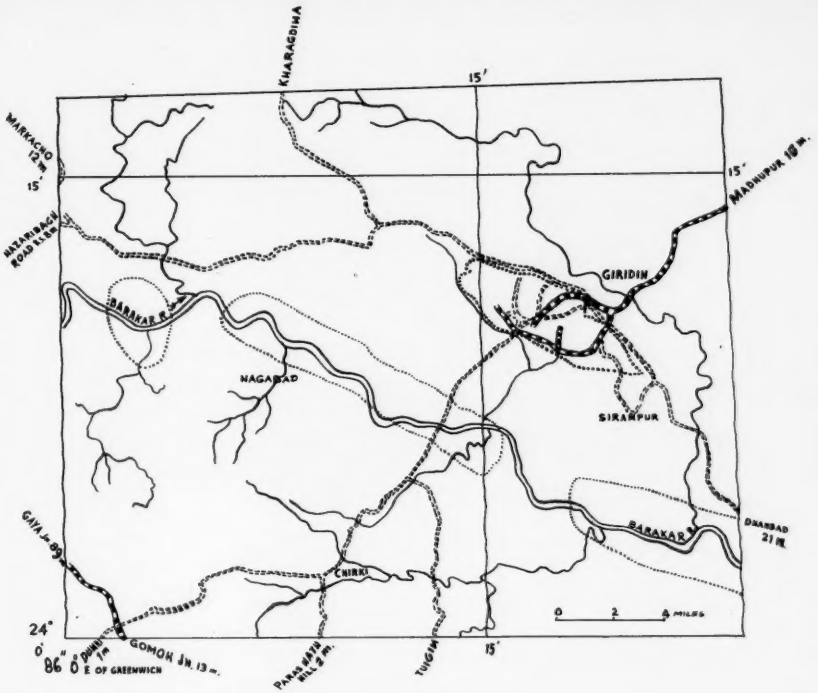

FIG. 2.—*Location map of Giridih.*

kars (Feistmantle, 1886; Fox, 1934).

The *interbedded fine sandstones* are green- to buff-coloured and may be regarded as subgreywackes. The grain size is quite uniform. The cementing material consists chiefly of chloritic matter and shale fragments. Most of the quartz grains show a crushed nature and are fairly clear of inclusions.

The topmost beds are coarse, greenish sandstones. Except for their colour and their apparent conformable nature with the needle shales, these might have been classified with the overlying Karharbaris. Quartz shows angular to subrounded edges. The cementing material consists essentially of greenish chlorite and altered mica, which is sometimes bent around the edges of quartz grains.

The Talchirs are always observed to dip away from the metamorphic boundary. Of the types mentioned the needle shales are by far the most predominant and constitute the type rock of the stage. The thickness of the needle shales ranges between 200 and 300 feet while the boulder conglomerate and the top coarse sandstones do not exceed more than 50 feet.

KARHARBARI STAGE

Lithology and Stratigraphy

The rocks of the Karharbari Stage rest unconformably on the Talchirs, the two being separated by a thin bed of conglomerate. The chief rock types consist of alternating grey, coarse, conglomeratic sandstones, grey and black arkoses, bluish and reddish brown micaceous shales, carbonaceous shales, and coal seams in that order. Shales are subsidiary, occuring as thin lenses interbedded with arkoses. The upper layers tend to be more conglomeratic, containing well-rounded pebbles of quartz and occasional orthoclase fragments.

The sandstones, in general, range from coarse conglomeratic sandstones to uniform,

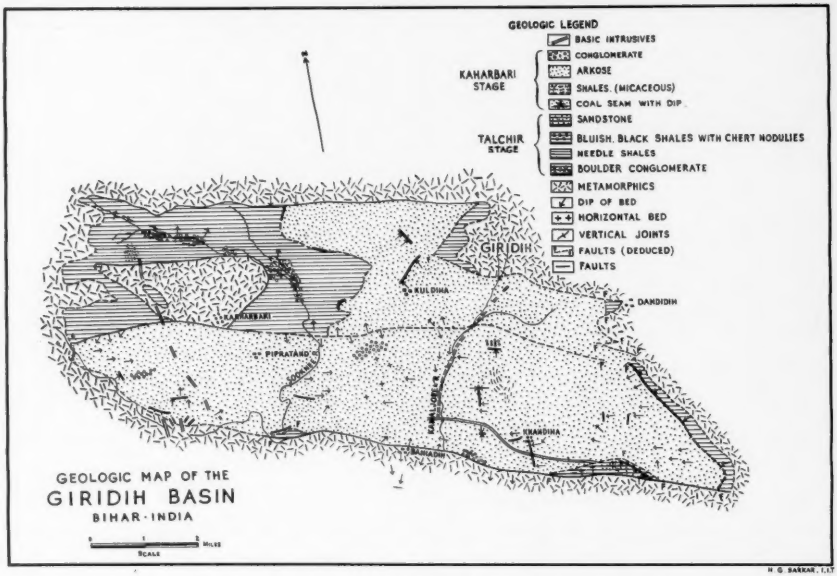

FIG. 3.—Geologic map of the Giridih Basin, Bihar, India.

medium-grained arkoses, the sub-rounded quartz grains being cemented by kaolinitic material. The sandstones commonly are much coarser than the corresponding Talchirs, although it is difficult to detect any systematic variation in the grain size. Cross bedding is widespread. Clastic dykes are sometimes found, particularly in the middle strata (Rao, 1956a).

The shales belong chiefly to the micaceous and carbonaceous variety, the sandstones themselves being flaggy at places, associated with finer grain size. The coal seams (fig. 4), in general, are underlaid by clayey, micaceous shales, but the junction between the roof of the coal seam and the overlying arkose is usually quite sharp.

PETROLOGY OF THE SANDSTONES

The sandstones of the Talchir and the Karharbari Stages represent three distinct petrographic types: the Talchir sandstones fall under the general category of subgreywackes, while the dominant types of the Karharbaris may be grouped as coarse grits and arkoses (Pettijohn, 1949). In addition to the clay and chloritic matrix, the subgreywackes usually contain subordinate amounts of secondary calcite. Modal compositions of some typical sandstones belonging to the two stages are presented in table 1.

Quartz—The quartz grains in the Talchir sandstones are angular and show a crushed nature and wavy extinction due perhaps to their derivation from metamorphic source materials. Bokman (1952) measured the elongations of several hundred grains from metamorphic and igneous source rocks and concluded that there exists a definite statistical difference in shape. He found that on the average, the grains from the metamorphic sources are more elongated. (Elongation is defined as the ratio between the long and short axes of the grains in a thin section.) From the modal analyses, it can be seen that the amount of quartz present in both the stages is relatively small. The percentage varies from 18.3 and 29.6 in the Talchirs and from 22.0 and 47.0 in the Karharbaris, the rest being made up of the matrix. The matrix consists of green chlorite in the former and kaolinite and altered feldspar in the latter. The high content of the matrix in both the stages is believed to be due to the weathered condition of the sandstones.

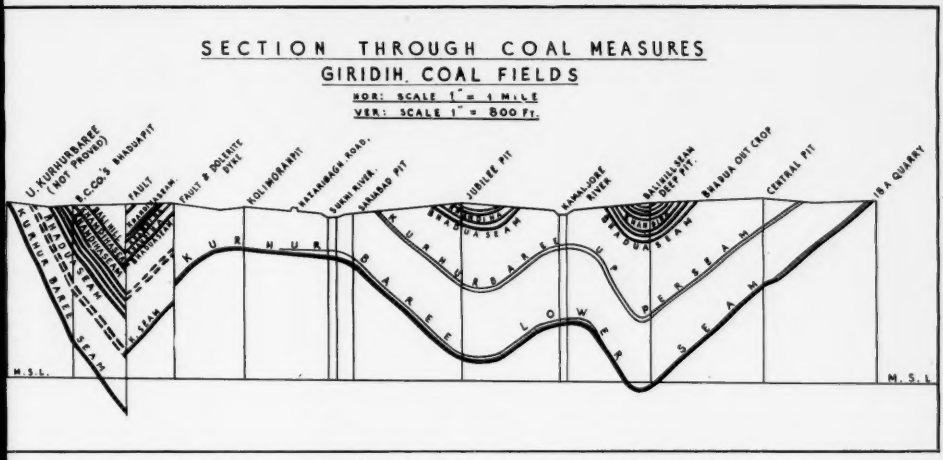

FIG. 4.—Section through Coal Measures of the Giridih Basin.

Feldspar—Feldspars, mainly orthoclase and microcline, constitute 4% to 9% of the Talchir sandstones. The amount increases in the coarser gritty type which contains up to 31% of the mineral. In the Karharbaris the variation in the feldspar content is largely due to their weathered condition. The freshness and comparatively unweathered condition of the feldspars in the Talchir stage is in complete contrast with those of the Karharbari stage. The phenomenon is believed to be due to the intense cold conditions which retarded effective weathering at the time of the deposition of Talchirs (Fox, 1934). Post-depositional features such as the development of secondary quartz, authigenic growths on zircon and tourmaline, and etched garnets are quite common in the Karharbaris but not in the Talchirs (Rao, 1956 b).

Sphericity

Sphericity determinations were made for fifty grains per sample on the average from the two stages after carefully splitting the samples. The standard Wadell technique modified by Krumbein and Pettijohn (1938) was used. By means of the micrometer eye piece the long and short diameters of the grains were also measured and the values were plotted in the Hagermann's scatter diagrams to find out the shape of distribution of the grains. Table 2 presents the average sphericity of the grains. The sphericity values for both the stages are quite high. The values range from 0.67 to 0.92 in the Talchirs and from 0.71 to 0.94 in the Karharbaris. The scatter diagrams (fig. 5) of the two stages describe a roughly elliptical area and show a certain comparison in their shapes. They thus indicate a more or less

TABLE 1.—*Mineralogical composition of the Talchir and Karharbari stages*

No.	Constituents	Talchir Stage			Karharbari Stage							
		4/146	4/147	4/314	4/400	4/413	4/64	4/29	4/411	4/486	4/52	4/407
1	Quartz	18.3	20.1	29.6	44.4	22.4	40.8	47.0	36.3	34.7	43.9	22.0
2	Orthoclase, microcline	3.9	8.9	30.6		15.1	31.5	11.9	3.9	4.8	0.9	27.9
3	Plagioclase							1.6		0.4		
4	Matrix; iron oxide, micas	75.6	71.0	39.7	55.6	62.5	27.7	39.5	59.8	60.1	55.2	50.1
5	Calcite	2.2										

TABLE 2.—*Sphericity of grains in the Talchir and Karharbari stages*

Stage	*Average sphericity* ϕ
Talchir	0.80
Karharbari	0·83

similar set of conditions of deposition for both the stages.

Grain Size Distribution

Mechanical analysis was carried out for 15 typical sandstones from both stages. No attempt was made to subdivide the 200 mesh (A.S.T.M. sieves) and the results were presented in table 3.

Both the stages show a uniform unimodal grain distribution, although a few specimens tend to show a minor secondary peak in the coarser grades in the Karharbari stage. The Talchirs present a maximum peak in the medium size range (0.5 to 0.25 mm), while the Karharbaris show a conspicuous peak in the relatively coarser grades (0.75 to 0.35 mm). The median grain size for the Talchirs averages 0.34 and ranges between 0.24 and 0.53 mm. For the Karharbaris the average median value is 0.44 mm, and the median ranges between 1 mm and 0.38 mm. The slightly coarser conglomeratic horizons show double maxima, one minor one in the coarser (1.41–1 mm) grades and the other in the medium size grade (0.5–0.25 mm). There is no striking modal class in either of the stages except in one sample in the Karharbaris, where most of the material was retained in the 1 mm class, and the histograms show an almost regular grain distribution. The differences are mainly in the position of the median. The relatively high weight percentages in the <0.088 mm range result from the high content of fragmented and highly weathered feldspar. The quantity is greater in the more highly weathered specimens than in the fresh ones.

Cumulative curves (fig. 6) are quite steep and indicate a well-sorted nature of the sediments of both stages. The sorting coefficient So was calculated using Trask's formula. Table 3 lists the mechanical composition and the significant size parameters of the sandstones.

The So value for the Talchirs ranges from 1.39 to 1.58 while the Karharbaris show a range from 1.3 and 1.72. All the values fall under the well-sorted class of 2.5 given by Trask. Arithmetic quartile skewness (Sk), a rarely used attribute, was determined for both the stages. Even though its full significance is yet to be understood, it certainly appears to have genetic importance. Gripenberg (1934) found that a sediment deposited by a uniform current shows a corresponding increase in the skewness in the direction of the current. The Talchirs are positively skewed while the Karharbaris indicate a negative skewness, although the finer-grained varieties of the latter show a slight skewness on the positive side. Apparently there seems to be greater admixture in the finer fractions of the Talchirs and in the coarser grades of the Karharbaris.

The sandstones of both stages are unimodal with a few exceptions in the Karharbari stage. The secondary mode is usually in the 2–1 mm range. The general unimodal distribution and the highly sorted nature of the sediments perhaps reflect conditions of deposition in a uniform current.

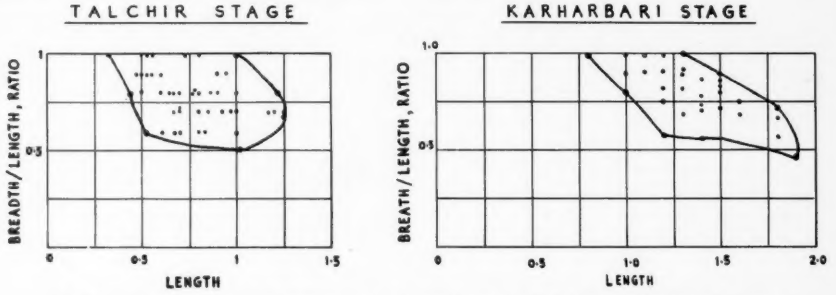

FIG. 5.—Hagerman plot of quartz grain shapes from the Talchir and Karharbari Stages.

Heavy Minerals

Heavy minerals were separated using the standard techniques (Krumbein and Pettijohn, 1938). The material was taken from the 0.5 mm grade and instead of the conventional separating funnel, jeffreys centrifuge tubes were used, with bromoform as the heavy liquid. The separations were observed to be much cleaner and less time consuming by this method.

In the Talchirs, the percentage of the heavies ranges between 0.32% and 4.3% with an average of 1.3%, while in the Karharbaris the range is from 0.22% to 2.46% with an average of 0.76%.

Differences in the regional distribution of the heavy minerals are main factors in delineating petrographic provinces. Comprehensive study of the heavy minerals coupled with the detailed field studies afford interesting clues as to the provenance of the source rocks. Doeglas (1940) found that near the source, pure heavy minerals are the rule, while farther away from the basin the heavy minerals become more and more complex due to their derivation from different sources.

The essential differences in the heavy mineral suites of the Talchirs and Karharbaris are the absence of green spinel and hornblende in the former and the disappearance of chlorite and epidote from the latter. In the Talchirs the euhedral zircon and tourmaline show fairly rounded edges. The former exhibit concentric black bands parallel to the prismatic and pyramidal faces in ordinary light. Fractures are common, usually perpendicular to the prismatic edges. Zircon and tourmaline in the Karharbari stage show less rounded edges, and perfect euhedral crystals are not uncommon. Zoning in zircons is absent. Rutile, a common mineral in the Talchirs, makes only a sporadic appearance in the Karharbaris (table 4).

Garnets in both the stages are subdivided on the basis of colour, namely pink, colourless, brown and yellow, the last-mentioned being of rare occurrence. Flooding of garnets has been noticed in three well-defined horizons; one in the Talchirs (Upper stage) and two in the Karharbaris (Middle and upper stages) constituting nearly 60% to 80% of the heavy mineral suite.

Careful examination shows a fundamental

TABLE 3.—*Mechanical composition of Talchir and Karharbari sediments*

Stage	Sample No.	Percent by weight in grade size										Statistical constants						
		>1.00	1.0–0.71	0.71–0.50	0.50–0.35	0.35–0.25	0.25–0.177	0.177–0.125	0.125–0.088	0.088–0.074	<0.074	Q1	Md	Q3	Qda	Ska	Sk	So
Talchir	4/326	—	—	0.7	20.6	26.3	26.2	13.4	6.8	4.0	1.7	0.172	0.25	0.33	0.079	+0.001	0.91	1.39
	4/146	9.0	20.8	23.8	18.4	8.8	6.8	3.6	2.4	1.8	4.2	0.31	0.525	0.77	0.23	+0.025	0.87	1.58
	4/147	—	—	—	16.6	30.6	22.2	8.2	4.8	4.3	13.2	0.143	0.24	0.315	0.086	−0.011	0.78	1.49
Karharbari	4/81	3.6	30.1	34.2	15.0	6.4	4.4	1.9	1.8	0.9	1.6	0.43	0.63	0.77	0.17	−0.03	0.83	1.34
	4/376	13.0	13.6	19.8	27.7	10.1	6.8	4.1	1.7	1.7	1.2	0.34	0.485	0.72	0.19	+0.045	1.04	1.46
	4/61	54.0	16.0	6.0	8.0	4.0	4.0	2.0	1.0	2.0	3.0	0.563	1.0	1.164	0.3	−0.137	0.66	1.44
	4/353	11.5	9.4	16.5	23.1	13.8	9.3	4.7	3.5	2.8	5.4	0.24	0.42	0.65	0.21	+0.025	0.86	1.65
	4/34	50.5	17.6	10.3	6.6	2.9	2.5	1.5	1.3	1.3	5.5	0.56	1.00	1.65	0.55	+0.105	0.92	1.72
	4/400	5.5	11.3	22.8	27.1	10.0	6.3	4.5	2.5	3.2	6.9	0.275	0.44	0.60	0.113	−0.003	0.85	1.48
	4/182	4.6	11.2	22.9	25.9	11.2	6.6	9.3	2.0	6.3	| | | |	0.255	0.45	0.58	0.163	−0.033	0.73	1.51
	4/94	0.3	5.4	30.8	32.2	10.6	6.3	3.3	2.2	8.9	| | | |	0.295	0.44	0.56	0.133	−0.013	0.85	1.38
	4/17	0.7	6.5	17.5	31.6	16.3	9.3	4.4	2.7	11.0	| | | |	0.235	0.38	0.50	0.133	−0.013	0.81	1.46
	4/128	32.9	23.2	13.1	8.5	3.9	3.2	2.2	2.4	10.6	| | | |	0.39	0.77	1.06	0.335	−0.045	0.67	1.65
	4/154	—	5.9	28.5	34.7	11.8	5.7	3.0	2.1	8.2	| | | |	0.30	1.46	0.51	0.105	−0.005	0.71	1.30
	4/156	0.8	15.3	35.7	24.6	6.7	4.7	2.6	1.9	7.7	| | | |	0.36	0.50	0.61	0.125	−0.015	0.88	1.30

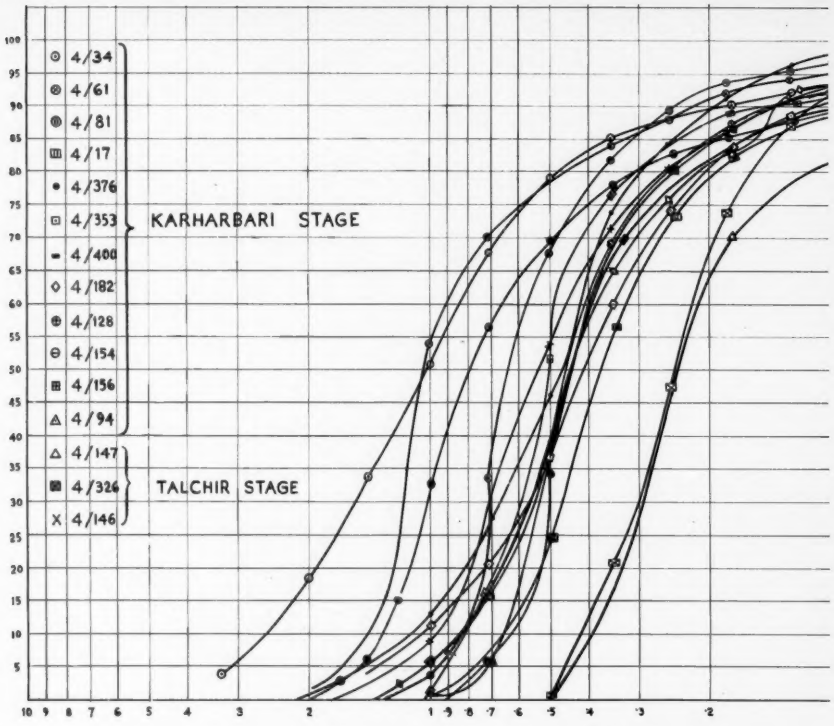

FIG. 6.—Cumulative curves showing mechanical composition of the sandstones.

difference in the nature of the garnets in both stages, which could be of correlative importance. Talchir garnets are clouded and have well-modified edges. Garnets in the Karharbaris stage are angular, and possess sharp hackly edges. The grains are transparent but strongly etched (Rao, 1956 c). Etching of detrital garnets has been noticed by several authors (Bokman, 1953; Smithson, 1941).

Mineralogy

Zircon—Euhedral as well as irregular grains, colourless and much fractured. The majority are clear and purple. Green varieties are present occasionally. Inclusions are mainly gaseous, but zircons themselves are sometimes present as inclusions. Euhedral grains have almost always slightly modified edges. Secondary growths on the prism are quite frequent in the Karharbari stage but not in the Talchirs. As noted previously, zircons in the Karharbari stage show concentric rings.

Tourmaline—Three varieties are recognized on the basis of colour; namely brown, bluish black and colourless. The bluish black grains are usually angular, and irregularly shaped, while the brownish variety is euhedral with slightly rounded edges. Inclusions are mainly magnetite. They are concentrated at the centre of the grains or more often evenly distributed throughout the grains, imparting to the grains a certain amount of cloudiness. Some exhibit deep brown pleochroism with greenish tint at the edges. Solution effects in the form of hackly edges are sometimes met with in the Karharbari stage.

Garnet—Colourless, pale pink, and brown varieties are most common, colourless and pale pink being predominant in Talchir and

TABLE 4.—*Heavy minerals of the Talchir and Karharbari Stages*

Stage	Sample No.	Magnetite Ilmenite	Zircon	Tourmaline	Rutile	Spinel	Garnet	Chlorite	Epidote	Hornblende	Corundum?	Mica
Talchir	4/326	7	2	—	—	—	8	1*	1	—	—	1
	4/146	7	4	4	—	—	4	5	—	2	3	5
	4/147	7	6	3	2	—	4	3	—	—	1	6
Karharbari	4/29	6	3	4	—	—	7	—	—	3	—	5
	4/23	8	4	4	—	1	6	—	—	4	—	5
	4/77	7	5	6	—	2	3	—	—	4	—	7
	4/81	6	5	5	1*	1	1	—	—	4	—	7
	4/160	7	5	2	—	—	7	—	—	1	—	5
	4/353	6	6	2	—	1	6	—	3	4	—	7
	4/411	7	4	5	1	1*	2	—	2	4	2	7
	4/376	4	1*	1	1*	—	8	—	—	1	—	1*

* One grain only.

Karharbari stages respectively (table 5). The grains are fresh, transparent, and possess a faint conchoidal fracture. The Talchir garnets are not etched, while the garnets in the Karharbari stage are strongly etched. The same rhombic pattern, observed by Smithson (1941) and Bokman (1953) has been noticed in the present case also. The regular gradation, however, is absent in these grains.

The presence of etched garnets and authigenic growths on the zircon and tourmaline, with the frequent hacksaw-edged pattern in the latter, demand conditions which permitted vigorous solution at the time of Karharbari sedimentation. The Talchir sandstones appear to be quite free of these effects, possibly due to the glacial climate, which retarded effective solution (Rao, 1956b).

Rutile—Elongated, oval-shaped with a deep yellow to reddish brown colour. The grains are prismatic and subrounded.

Spinel—Dark green, opaque, and isotropic pleonaste is present in small quantities.

Magnetite and Ilmenite—Except where there is flooding of garnets, these opaque minerals constitute 40%–50% of the total heavy mineral suite. Magnetite occurs as irregular, opaque, black grains. No attempt has been made to distinguish between the two.

Hornblende—Angular, irregular, and dark brownish-green grains, quite fresh and unaltered. The grains are quite opaque except for the green colour at the edges.

Epidote—Greenish-yellow grains with marked pleochroism and red and brown patches of alteration.

Chlorite—Pale yellowish-green, cleavage fragments with blotchy colour, irregular shape and weak birefringence.

Micas—Muscovite is chiefly represented. Inclusions consist of magnetite, zircon and tourmaline.

RECONSTRUCTED PICTURE OF SEDIMENTATION

The lower Gondwana rocks of the Giridih Basin form only a part of what is known as the Gondwana System, the chief coal-bear-

TABLE 5.—*Percentage of garnet types in the Talchir and Karharbari stages*

Stage	Sample No.	Garnet type (percent)		
		Colourless	Pink	Brown
Talchir	4/326	66	15	7
	4/146	3	3	—
	4/147	3	1	—
Karharbari	4/29	—	51	4
	4/23	—	16	—
	4/77	1	2	—
	4/81	—	1	—
	4/160	—	47	—
	4/353	—	16	—
	4/411	1	—	—
	4/376	5	8	2

PLATE 1

A.—Unstratified conglomerate of the Talchir Stage, interpreted as tillite. (Photograph by J. L. Hough).

B.—Stratified conglomerate of the Talchir Stage, interpreted as glacial outwash. (Photograph by J. L. Hough).

ing formations in India. A detailed account of the system has been given by Fox (1931). The rocks are developed in peninsular India roughly in an inverted triangular pattern, the eastern edge of which is marked by the east coast extending from the Godavari Valley to the Mahanadi Basin. The Giridih Basin is in alignment with the Damodar, Narbada, and Son Valleys with an east-west trend. In this triangular area the Gondwana rocks are found in faulted troughs. There is much controversy regarding the age of these faults. It is the opinion of the older workers (Fox, 1934), that the faulting took place contemporaneously with the deposition of the sediments. It is firmly established that the faults in the Damodar Valley are older than the intrusives and thus were the result of a much earlier tectonic activity. Dr. Jowit's (Fox, 1934) work in the Karanpura coal field revealed the presence of two sets of faults, one pre-Mahadeva and another post-Mahadeva (Triassic). In the Giridih Basin the trap dykes have intruded along the plane of the southern boundary fault which is in accordance with the findings in the Damodar Valley. Jacob (1952) remarks that the widespread block faulting was probably initiated towards the close of the late Carboniferous glaciation but was most active in the Jurassic period.

In Giridih, the sedimentation started with the boulder conglomerate. Part of the conglomerate is unstratified and therefore has the appearance of true glacial till deposited directly by glacial ice (plate 1, fig. A); a part is stratified and therefore has the appearance of glacial outwash. It could therefore be interpreted that glacial ice has actually covered the area and brought in the unstratified material; that the ice front then retreated, but while it was still nearby the water running off from it deposited the stratified sand and gravel perhaps in shallow water or at least very close to the ice. The alternating coarse and fine sandy layers and alternating sand and gravel in the boulder bed (plate 1, fig. B) are perhaps indicative of variations in the rate of melting of the glacial ice and therefore of variations in the quantity of discharge of melt water. The occurrence of the needle shales overlying the boulder bed then suggests that the ice front retreated farther from the depositional site leaving behind a lake basin. The boulders in the needle shales probably were rafted from the more distant glacial ice while frozen in floating blocks of ice and were dropped into the lake when the ice blocks melted. It therefore appears more probable that the deposition of needle shales was due more to the glacial retreat than to the actual deepening of the basin. Variations in the grain size in needle shales can be explained as resulting from two factors: (1) variations in the quantity and velocity of flow of melt water, and (2) Increasing distance between the depositional site and the receding ice front. Much work still remains to be done as to the direction of movement of ice and it is hoped that an examination of the neighbouring basins will be of much help in that direction.

During the close of the Talchir period, the lake basin began to rise and the coarse Talchir grits overlying the needle shales indicate conditions almost similar to those that existed in the Karharbari times. The thin conglomerate on top of the Talchirs is probably indicative of the complete emergence of the depositional site.

The environment in the Karharbari times was essentially that of rapid erosion and quick burial. The whole of Karharbari sedimentation was one of arkosic deposition, punctuated by several cycles of coal formation. Barton (1916) made a detailed study of the arkoses and classified them according to their genesis. He concludes that "the deposits are of such different types and different associations ranging from coal measures, mud cracked red beds with beds containing faceted pebbles, marine fossils, etc. that the old conception of limiting the significance of arkoses is manifestly incorrect." The present arkoses, in accordance with his views, signify conditions of moist, chiefly temperate climate. The arkose is greyish, composed of subangular grains of quartz and considerably decomposed feldspar in a matrix of argillaceous material and kaolin and at times carbonaceous matter (Rao, 1956b) and carrying a large number of plant fossils, abundant in the carbonaceous and red shale horizons. Gritty and conglomeratic beds are quite frequent. The arkoses of Giridih Basin fall under the class of tectonic arkoses (Pettijohn, 1949) which suggest a rising source

area either by upfaulting or uplift and a sinking depositional site by down faulting. The arkoses are cross bedded; the cross bedding is simple and similar to that which forms in an advanced terrace constructed by a stream or a shallow water current. The convex lobes point towards the east and indicate a west to east drainage (Shrock, 1948). The almost negligible rounding of the heavy detritals zircon and tourmaline in the Karharbari stage indicate a nearer source area. It seems quite probable that a prominent positive area existed to the west very near the depositional site in the Karharbari times. The level of water in the Karharbari rivers oscillated considerably due to the unstable conditions of the shelf. The paucity of shales in the Karharbari strata perhaps indicates that the basin was never very deep nor was the water sluggish.

ACKNOWLEDGEMENTS

The author expresses his grateful thanks to Prof. J. L. Hough for his guidance in the field and in the initial stages of the laboratory investigation and for his critical rendering of the manuscript. He is deeply indebted to Prof. T. C. Bagchi, Head of the Department of Geology and Geophysics, Indian Institute of Technology, for his constant encouragement throughout the progress of work. He acknowledges with thanks the kind help rendered by the Superintendent of the Collieries, Baniadih, Giridih P.O., during the course of his field investigations.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 4, PP. 447–452
FIGS. 1–3, DECEMBER, 1957

APPOSITIONAL FABRIC STUDY OF THE COASTAL SEDIMENTARIES, EAST GODAVARI DISTRICT, ANDHRA, INDIA[1]

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ABSTRACT

The sedimentaries of the coastal region of the East Godavari district are studied by appositional fabric analysis to derive the direction and nature of the agent of deposition. Considerable part of the work is devoted to develop techniques of processing the sandstones for dimensional analysis. A circular scale is devised for measuring the flow directions of the grain outlines. The results indicate that the agent of deposition is a wave and that the sediments were transported towards north on the east coast of India during the Upper Jurassic as is the case today.

INTRODUCTION

The sedimentary rocks of the coastal region of the East Godavari and Visakhapatnam districts were studied by Mahadevan and Sriramadas (1952). They concluded from the results of heavy mineral analysis that the sedimentaries are more like the Upper Jurassic than Lower Jurassic or Tertiary. The present work is a study of the appositional fabric of these sedimentary rocks to get the direction and nature of the agent of deposition and thereby their inter-relationship.

The area is located between north latitudes 17° 12′ and 17° 23′ and longitudes 82° 24′ and 82° 42′, in portions of Survey of India topographic sheets Nos. 65 K/7, 65 K/8 & 12 and K/11, (on the scale of one inch to one mile).

FIELD STUDY AND DESCRIPTION

The size and distribution of outcrops, directional variation in lithology, grain size, and trend have been carefully recorded. Representative specimens are collected from different outcrops. On each of the specimens the geographical direction and any other directional property present in the specimens are marked.

The sedimentary rocks are in the nature of sandstones with varying proportions of argillaceous and ferruginous matter. The outcrops are now found as small detached patches, distributed within a short distance of one to four miles from the coast. They are roughly elliptical in outline and rise commonly to about 15 feet and occasionally to about 50 feet height from the ground. All the outcrops are below 100 feet M.S.L. The basement of these sedimentaries is khondalite gneisses (Precambrian) as is apparent from the well sections.

The grain size of the sandstones shows great variation in vertical as well as horizontal extent. At Ayaparaz Kottapally (Lat. 17° 15′; Long. 82° 26′ 30″) the sandstones cropping out on a hillock are very coarse and devoid of heavy minerals. They are fine-grained in some of the quarries lower down. About a fourth of a mile west of this hill the sandstones are usually fine-grained with local variations to gritty and conglomeratic types. At Gunupudi (Lat. 17° 20′; Long. 82° 38′ 30″) conglomerates with pebbles of about an inch to two inches in diameter are found at an altitude of about 40 feet M.S.L. and these are nearest to the coast in the area.

APPOSITIONAL FABRIC ANALYSIS

In the clastic sediments, the appositional fabric results from the dimensional orientation of the constituents, mainly brought about by forces operating on the sediment during deposition, and left almost undisturbed during and subsequent to consolidation. These rocks are free from effects of dynamic earth movements. Hence, from the appositional fabric analysis of these rocks, an attempt is made to determine the direction and nature of the agent of deposition. The basic principle in these determinations is that the ellipsoidal detrital grains orient with their major axes parallel to the line of flow and with their broad ends pointing upstream. The major axes and the broad ends of the ellipsoidal grains together define the

[1] Manuscript received November 12, 1956.

direction of flow of the agent of deposition as explained by Dapples and Rominger (1945).

Direct determination of the major axes and recognition of the broad ends of the detrital grains is possible in the case of the conglomerates (Krumbein, 1939). But in fine-grained sedimentary rocks, where such direct measurements are not possible as in the present investigation, the counterparts of required directions can be located within the projection of the grains as defined by their intersections with the bedding plane. Such a two-dimensional picture of the grain projections depicts with a reasonable degree of accuracy the original preferred orientation of the grains in the rock. The projected picture of the grain outlines can be obtained by photographing weathered specimens with the grains slightly free and protruding above the bedding plane (Dapples and Rominger, 1945).

Processing the Bedding Surface of the Specimens

In the absence of such suitable weathered specimens, the author has adopted three methods to prepare the bedding surface for taking photographs of the grain outlines. Each method differs from the other in processing the bedding plane of the specimen. In the first method, the fresh bedding plane is subjected to artificial removal of the cementing material. This leaves the grains standing out when a clear photograph of their outlines can be taken. The relief of the grains is much improved by increasing the colour contrast between the grains and the cementing material by suitably staining the the latter. The cementing material is aluminous; therefore the stain used is alizarin blue. In the ferruginous sandstones, the contrast is very much less between the transparent to translucent quartz grains, and the surrounding cementing material. The contrast is improved by slightly leaching the iron oxide in the cementing material of the bedding plane. Such leaching renders binding material surrounding the grains colourless and leaves material below the grains coloured, bringing thereby the required contrast.

In the second method specimens with highly resistant binding material are ground parallel to the bedding plane whereby the grain outlines are seen clearly.

In the third method, a large thin section is cut parallel to the bedding plane, and is ground. The grains show great contrast over the surrounding opaque cementing material in transmitted light.

Each method has certain advantages and disadvantages with regard to clarity with which the grain outlines can be photographed and to the time consumed in processing the specimen. In the first method, the clarity is very much less but it takes the least time for conditioning, and therefore is of great advantage where a number of specimens are to be studied. In the second method the clarity is better and it appears to be the easiest and the least time-consuming for specimens with resistant cementing material. The clarity is best under the third method, but the process is laborious and time-consuming and therefore is suitable for working with only a few specimens.

Obtaining the Grain Outlines

The grain outlines of the specimens are obtained in many ways. The polished or processed specimens are mounted on plastacine to keep them horizontal, and placed under the diascope. Sufficiently enlarged projections of the grain outlines are traced. Alternately, the polished or processed specimens are directly photographed and the negative used in conjunction with the episcope to get an enlarged picture of the grain outlines. The grain outlines are traced from the episcope projection in the case of the large thin section of the rocks. But to take a contact negative of the thin section and project it with the episcope is found more convenient.

Marking the Flow Directions of the Grain Outlines

In the map of the grain outlines, the major axes and the broad ends have to be marked to determine the flow direction of the agent of deposition of the grains. From the theoretical soundness and practical applicability the "least projection elongation" and "area direction" as defined by Dapples and Rominger (1945) have been found to be suitable to delineate the flow directions in the projected picture of the grains and hence they are used in the pres-

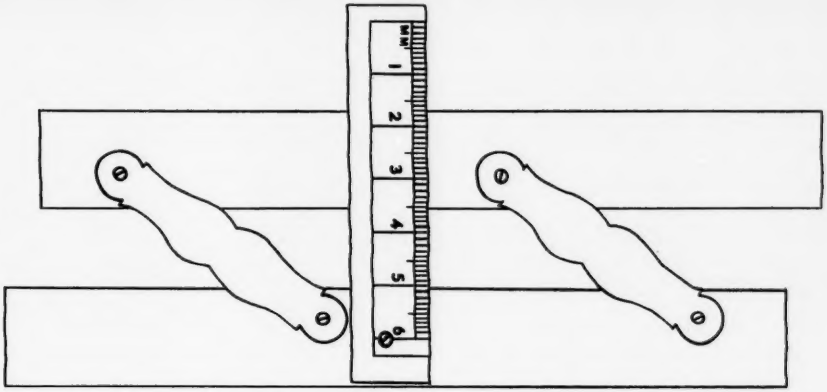

FIG. 1.—A convenient form of parallel rule to mark the "least projection elongation and area direction."

ent case. The least projection elongation is a line parallel to a pair of parallel tangents to the grain projection with a minimum distance of separation. This is drawn using a parallel rule to which the author has attached a small scale at right angles to measure the distance of separation of the pair of the parallel rule (fig. 1).

The area direction is that end of the grain projection which has lesser area outside the grain boundary but within the least projection rectangle as detailed by Dapples and Rominger (1945). This is fixed by drawing lines tangential to the free ends of the grain projection and perpendicular to the parallel tangents with the least amount of separation. The end of the grain projection, having lesser area outside the grain outline and within the rectangle formed by the tangents defines the area direction.

The least projection elongation defines the line of flow but the area direction defines which end of the flow line corresponds to the upstream. An arrow head, put to the end of the least projection elongation line defined by the opposite side of the area direction, indicates flow direction.

The above measurements can also be taken by the use of a circular celluloid scale with concentric circles at intervals of one millimeter (fig. 2). The author devised this to substitute conveniently the parallel rule for marking the least projection elongation and area direction. The scale is provided with a slit about one mm wide along the diameter ending just about five mm below the periphery and with a small notch at the centre.

The underlying principle in using the scale can be explained well by taking a limiting form of grain projection—namely an ellipse. The parallel tangents with the minimum distance of separation that can be drawn to the ellipse will be at right angles to the minor axis. The minor axis forms the diameter of the maximum inscribed circle within the ellipse at the points of contact. Therefore if this diameter is drawn the least projection elongation can be marked at right angles to this. The scale is placed over the grain projection and with slight manipulation the maximum circle that can be inscribed is located. The scale is rotated by inserting a pin at the notch, so as to make the slit pass through the points of contact of the maximum inscribed circle and the grain boundary, as located by the scale. The diameter is marked along the slit. A line drawn at right angles to this line will define the least projection elongation.

The area direction can also be located by the circular scale. It is indicated in the grain projection, by the least area end within the grain projection but outside the maximum inscribed circle. In the example cited where the grain projection is an ellipse with equal areas on either side of maximum inscribed circle, the area direction is undefined. But it is only a limiting case. In the grain projection different from this limiting

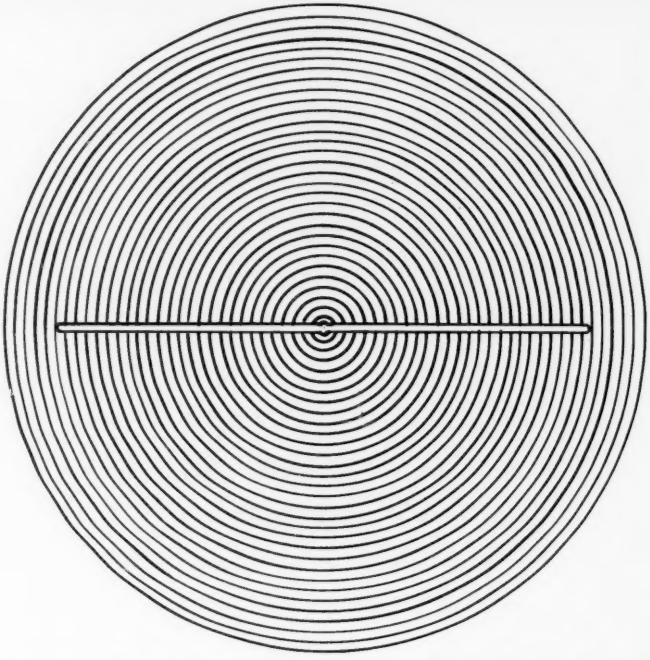

FIG. 2.—A circular celluloid scale to mark the "least projection elongation and area direction."

case, the area direction is marked, by visually estimating the least area outside the maximum inscribed circle and within the grain projection.

As the grain projection approaches a circle, the least projection elongation as well as the area direction become indefinite, being infinite in number. Also, as the projection approaches more perfectly an ellipse, the area direction becomes indefinite, being symmetrical. Therefore these two limiting cases of grain projections, where measurements are of little use in orientation analysis, may be left out in actual practice.

TABLE 1.—*Preferred orientation of sandstone grains*

Outcrop No.	Specimen No.	Percentage of grains oriented in each octant							
		0°–45°	46°–90°	91°–135°	136°–180°	181°–225°	226°–270°	271°–315°	316°–359°
I	1	26.30	21.04	10.52	2.63	5.32	13.15	10.52	10.52
	2	21.04	23.67	10.52	7.89	5.16	5.32	15.88	10.52
	3	13.15	28.93	7.89	5.33	13.15	13.15	10.52	7.89
	4	4.76	28.58	11.90	—	2.38	7.14	19.08	26.18
	5	25.71	20.00	—	—	8.57	14.29	17.14	14.29
	6	8.34	12.50	4.17	—	—	33.33	29.16	12.50
	Average	16.55	22.45	7.50	2.64	5.76	14.40	17.05	13.65
II	7	26.03	6.45	3.23	—	12.70	12.90	22.57	16.12
	8	14.28	17.14	20.00	5.61	15.53	13.14	8.57	5.73
	9	7.63	2.63	2.63	21.30	5.24	5.24	31.66	23.67
	10	15.38	10.26	2.56	—	—	12.82	28.20	30.78
	Average	15.83	9.12	7.10	6.73	8.37	11.03	22.75	19.08
I & II	Average	16.19	15.79	7.30	4.69	7.07	12.71	19.90	16.36

The Relative Position of Flow Direction of the Grains and the North

To measure the angle between the flow direction and the north, lines parallel to N-S line marked already on the map of the grain projections are drawn for all the individual grain projections so that they intersect the flow directions of the grains. Then the azimuth between the arrow head of the flow direction and the north point is measured in clock-wise direction and noted against each of the grain projections. As an illustration of the above measuring techniques the azimuths of about 500 grain projections of each one of the 10 specimens belonging to the two outcrops are determined. The angles are divided arbitrarily into eight groups with 45° for each group starting from zero at north. The total number of grains under each group is obtained. From this, the percentage of flow directions under each group is calculated. These percentages are given in table

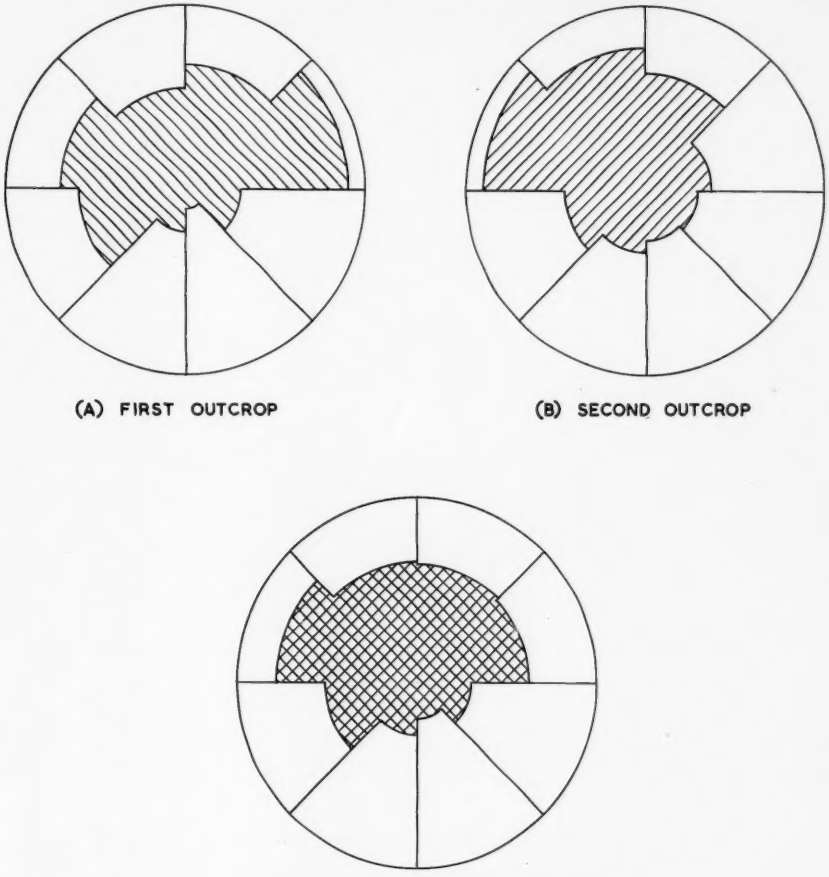

FIG. 3.—Flow directions of the sandstone grains. A, Average of the flow directions of six specimens in the first outcrop. B, Average of the flow directions of four specimens in the second outcrop. C, Average of the flow directions in the first and second outcrops.

TABLE 2.—*Orientation of sandstone grains —statistics*

Outcrop No.	Specimen No.	Resultant azimuth	Vector magnitude %	Chi-square
I	1	22°33′	32.06	33.95
	2	32°57′	31.21	27.42
	3	50°11′	13.74	29.44
	4	6°13′	12.47	67.73
	5	345°30′	38.96	47.95
	6	295°18′	48.75	70.99
	1– 6	356°53′	26.92	24.69
II	7	322° 7′	40.69	46.12
	8	285°42′	14.36	14.75
	9	296°25′	35.48	71.45
	10	328°11′	60.50	80.27
	7–10	322°26′	29.71	20.25
I & II	1–10	338°43′	26.98	16.94

1 and graphically represented below for ready visual comparison (fig. 3).

The azimuth and magnitude of resultant vector for each of the ten samples and composites of samples one to six, seven to ten, and one to ten are calculated (Curray, 1956a). The Chi-square test of significance against randomness is applied to each of the above samples and their composites. The azimuths and magnitudes of resultant vectors and Chi-squares are given in table 2 (Curray, 1956b). It is to be noted that to convert tan $\bar{\theta}$ value to the azimuth of the resultant vector, there is a choice of first or third quadrant and second or fourth quadrant. A reference to table 1 will make the first and fourth quadrants more probable than second and third quadrants.

THE SIGNIFICANCE OF FIELD AND LABORATORY DATA

The wide and frequent variation in mechanical composition of the sediment in the vertical and horizontal extent as outlined under field study suggests the agent to be wave or stream. The presence of fragmentary fossils in one of the patches lends support to the marine origin of these sandstones. The fossils are commonly fragmentary and extremely localized. This observation suggests that the sediments are in the nature of coastal deposits formed under shallow water, acted on by waves and littoral currents; it is of common observation that the marine shells at the breaker zone are always localized and fragmentary being handled by the waves over and over again before deposition.

Table 2 gives the resultant vector (azimuth and magnitude) and Chi-square for each of the samples and their composites. The observed values of Chi-squares with seven degrees of freedom exceed the critical value at 0.05 in all cases, making it extremely unlikely that the distribution is random. Hence it is inferred that there is preferred orientation. This preferred orientation is towards north, northwest, and northeast as shown by azimuths of resultant vectors. This preferred orientation towards north with limited oscillation towards northeast and northwest is one of the characters of a wave deposit.

This conclusion, namely that the depositional agent for these rocks was the wave, as conceived from the appositional fabric analysis, is in agreement with the observations from the field data. In addition, the appositional fabric analysis also shows that the sediments of the Upper Jurassic sandstones were moved roughly from south to north. This is of special significance because Mahadevan and Sriramadas (1948) drew the attention to the fact that littoral currents stow up sand from south to north along the east coast of India. This suggests that in Upper Jurassic times the littoral currents had a dominant northerly course as is the case today.

ACKNOWLEDGEMENT

I wish to thank Professor C. Mahadevan for his keen interest in and encouragement of the work. My thanks are due to the editors of *Sedimentary Petrology* for suggesting the statistical analysis of the results.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 4, PP. 453–459
FIGS. 1–4, DECEMBER, 1957

HYDROTHERMAL ALTERATION OF PHOSPHORIA MUDSTONES[1]

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ABSTRACT

Samples of phosphatic mudstone collected from several measured sections in the Retort Phosphatic Shale Member of the Phosphoria Formation near Divide, Montana, contain an abundance of montmorillonite, locally associated with kaolinite and talc. Of several possible modes of origin, hydrothermal alteration of pre-existing illite to montmorillonite best accords with related geologic phenomena, including the presence of intrusives within and/or adjacent to the formation, the associated hydrothermal alteration of the underlying dolomite to talc, the associated low-grade metamorphism of the phosphatic mudstone itself, the network of calcite and quartz veins within the mudstone, and the association of talc and montmorillonite. The kaolinite, which occurs in very carbonaceous mudstones, may be (1) further hydrothermal alteration of montmorillonite, (2) an authigenic mineral formed in a restricted part of the Retort Basin with acidic bottom conditions, or (3) a detrital mineral.

INTRODUCTION

The Phosphoria Formation (Permian) crops out over an area greater than 100,000 square miles in Montana, Idaho, Utah, Nevada, and Wyoming. In almost all except the most recent literature, the formation name applies to all the sedimentary rocks of Permian age associated with the phosphate beds. Recent work by the U. S. Geological Survey has resulted in the subdivision of the formation Phosphoria Formation into three formations, with eleven members (McKelvey et al., 1956). The name *Phosphoria Formation* is retained for that part of the section composed dominantly of phosphate rock, phosphatic shale, and mudstone. Following the recent nomenclature, the present study is concerned with the Phosphoria Formation on its northern outcrop boundary in Montana where the formation is divided into the Retort Phosphatic Shale Member and the Tosi Chert Member (fig. 1).

The Retort and Tosi Members are regarded as nearly time-equivalent facies of the same sea, the former having been deposited in the deeper part of a southwest trending marginal basin, the latter along the northeast shoreline (Rooney, 1956). The Retort Member is overlain by the resistant Shedhorn Sandstone (Permian) and underlain by the Franson Member (dolomite) of the Park City Formation (Permian). It ranges from 10 to 40 feet in thickness. Characteristically it is composed of soft, phosphatic, carbonaceous mudstone, phosphate rock, and shale. In thin section, irregular closely packed ovulites intermesh as though plastic before induration. Very few sand or silt grains occur. Fossil remains are not abundant.

The Tosi Chert ranges from several feet to 60 feet in thickness in the Whitehall area (fig. 1). It is composed dominantly of thin-bedded cherts which are generally ferruginous and dolomitic. It also contains thin beds of hard, siliceous oolitic phosphate rock, which range from a feather edge to four feet in thickness. The phosphate rock contains sand, silt, and abundant fossil remnants resembling sponge spicules or echinoid spines.

PREVIOUS WORK

Studies of the clay minerals in the Phosphoria formation of southwestern Montana are very few: Herr, 1955; Weaver, 1955; Fowler, 1955; Rooney, 1956; Moore, 1956. Herr's study, the only one devoted entirely to the clay minerals, indicates that illite and mixed-layer illite-montmorillonite are the dominent clay minerals in the Phosphoria of southwestern Montana. In two of the three localities studied by Weaver, kaolinite is dominant; in the other, illite is dominant. Fowler's determinations, made on samples from a small area, generally agree with Herr's. Rooney's determinations made on samples collected from the Tosi Chert Member in the Whitehall area also concur with Herr's. Both Moore's and Rooney's determinations of clay minerals in the Retort, or deeper water, facies of the Phosphoria Formation in the Divide area, however, show a surprising abundance of montmorillonite, locally associated with kaolinite and

[1] Manuscript received February 27, 1957.

talc. This paper describes the mode of occurrence and presents a theory of origin of these latter deposits.

GEOLOGY OF THE AREA

The area in which the present writer's samples were collected has been tightly folded. Faults are common; in fact, it is rare to be able to trace a bed more than 100 yards without finding at least a minor offset. Bedding faults, generally revealed only by trenching, are common in the nonresistant Phosphoria shales. The Boulder Batholith borders the region on the north (fig. 4). Numerous stocks and sills, many of them very extensive, suggest that the igneous basement is near the surface. The degree of deformation and intrusion, however, varies from one sample area to another and is least in the Trusty Lake area (fig. 1).

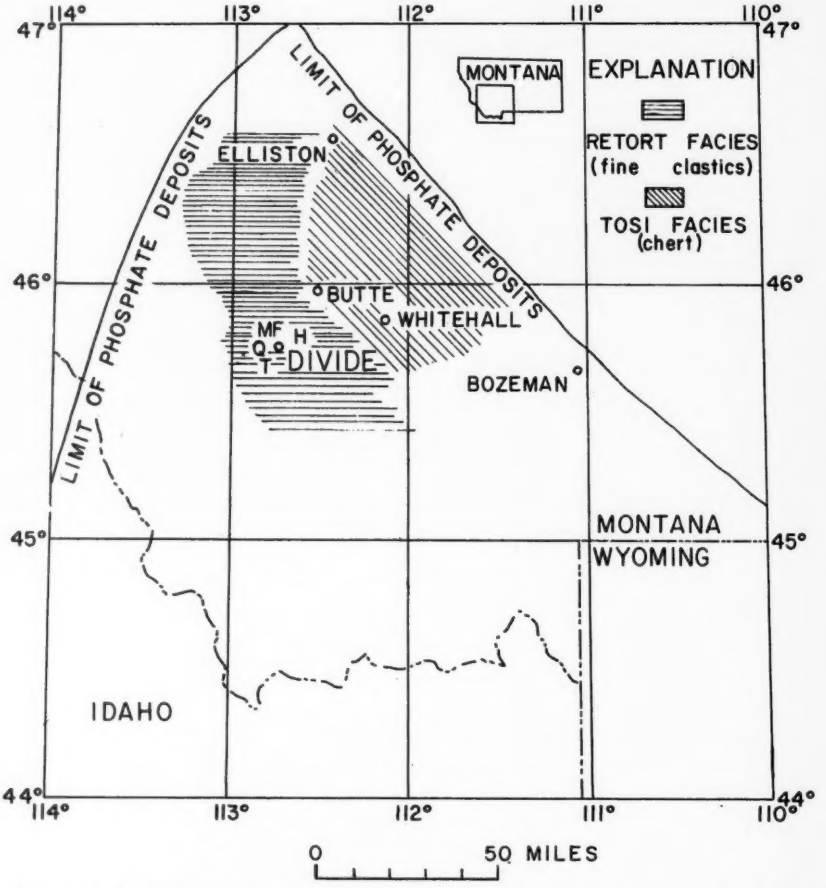

FIG. 1.—Index map showing the northern limits of phosphate deposits (after Swanson et al., 1953), the approximate distribution of the Retort Phosphatic Shale and Tosi Chert Members of the Phosphoria Formation in part of southwestern Montana, and the location of the Mount Fleecer (MF), Quartz Hill (Q), Trusty Lake (T) and Highland Mountains (H) areas.

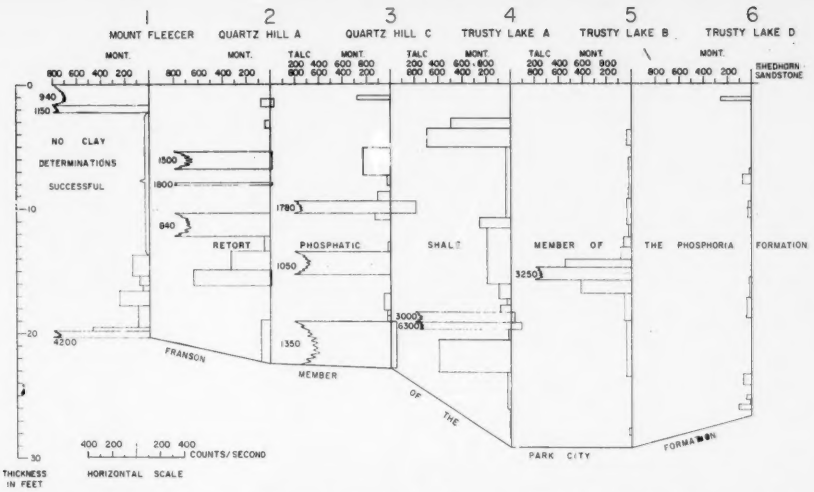

FIG. 2.—Relative intensities of basal reflections of montmorillonite and talc (after glycolation) in six stratigraphic sections of the Retort Phosphatic Shale member of the Phosphoria Formation near Divide, Montana.

METHOD OF STUDY

Except for the Highland Mountains section, the stratigraphic sections[2] were measured and sampled in detail in order to permit P_2O_5 analyses and commercial evaluation. The sections are made up dominantly of phosphatic mudstone, shale, and phosphate rock. Part of the crushed sample used for the P_2O_5 determinations was available for clay mineral determinations. Approximately 120 of these were prepared for X-ray diffraction analysis by the conventional settling-velocity method and X-ray determinations run on a XRD-3D General Electric spectrometer. (For a complete description of the procedure, see Murray, 1954.) X-ray patterns were made of the untreated samples and in most cases of glycolated and heated samples in order to distinguish montmorillonite and chlorite.

Because methods for the quantitative determination of clay minerals are still in a state of flux, the author feels that the intensities of the basal reflections, corrected for background, are the most useful data that can be given at the present time. In comparing intensities, however, one should be aware that kaolinite has a much better reflecting power (on the order of three times) than illite or montmorillonite (Murray, 1954, p. 58), and that glycol-expanded montmorillonite has a better reflecting power than illite (Johns, Grim, and Bradley, 1954, p. 242). The patterns produced by the glycolated slides of the $<2\ \mu$ fraction were used to obtain the intensities given on the accompanying graphs. The slides had been sedimented for 24 hours after the $>2\ \mu$ fraction had settled out.

RESULTS

The quantitative data are summarized in figures 2 and 3. Generalizations which can be drawn from these graphs are:

1.—Most samples from the Mount Fleecer and Quartz Hill sections show very strong montmorillonite reflections, whereas few

[2] The locations of the stratigraphic sections used in this paper are: (1) Mount Fleecer section, NE¼SW¼ sec. 14, T. 1 N., R. 10 W., Silver Bow County; (2) Quartz Hill A, E½NE¼ sec. 17, T. 1 S., R. 10 W., Beaverhead County; (3) Quartz Hill C, 500 feet south of Quartz Hill A; (4) Trusty Lake A, N½NE¼ sec. 32, T. 1 S., R. 10 W., Beaverhead County; (5) Trusty Lake B, NW¼ SE¼ sec. 33, T. 1 S., R. 10 W.; (6) Trusty Lake D, NW¼SE¼ sec. 3, T. 2 S., R. 10 W.; (7) Highland Mountains section, NW¼NE¼ sec. 32, T. 1 N., R. 8 W., Silver Bow County.

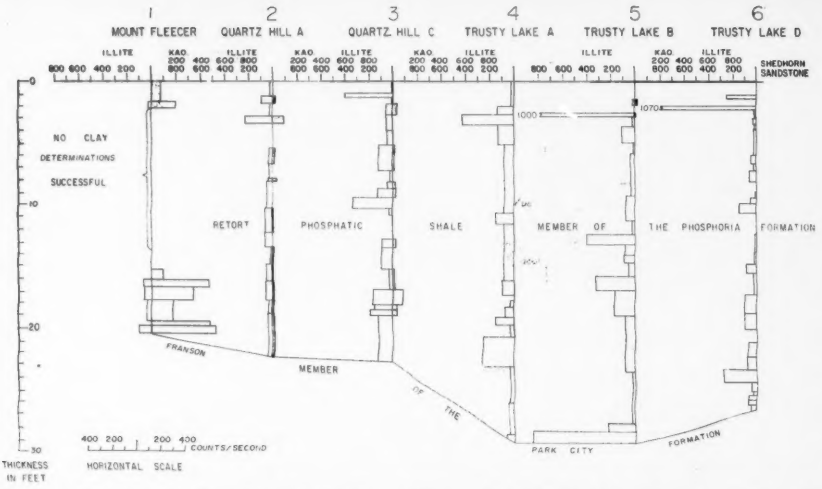

FIG. 3.—Relative intensities of basal reflections of illite and kaolinite in six stratigraphic sections of the Retort Phosphatic Shale Member of the Phosphoria Formation near Divide, Montana.

samples from Trusty Lake sections B and D show strong montmorillonite reflections.

2.—Kaolinite is almost totally confined to the Mount Fleecer and Quartz Hill sections and to samples having strong montmorillonite reflections.

3.—Talc, where present, is associated with strong montmorillonite reflections.

4.—Illite reflections are strongest in the Trusty Lake sections and Quartz Hill C.

5.—The beds cannot be correlated from one trench to another by the clay mineral content.

The Highland Mountains section, which is not plotted on the graphs because only six grab samples were collected, showed weak to strong montmorillonite reflections in five samples and weak to moderate illite reflections in two samples.

POSSIBLE MODES OF ORIGIN OF MONTMORILLONITE AND KAOLINITE

The presence of illite in the Phosphoria is not unusual and requires comment only with regard to its association with montmorillonite and kaolinite. The abundance of the latter two minerals in Permian deposits is unusual and must owe its origin to unusual conditions. Possible modes of origin are:

1. Weathering in place
2. Diagenesis
3. Original deposition
4. Volcanic activity
5. Hydrothermal alteration

Weathering in Place

Weathering does not appear a plausible explanation because the samples were collected from hand and bulldozer trenchs, often one within the other, cut deep into fresh rock. Furthermore, the mudstones are *relatively* impermeable and their black hue indicates that the carbonaceous matter has not been oxidized.

Diagenesis

Diagenetic alteration of other clay minerals to montmorillonite is unlikely because the reverse alteration is what has been observed (Grim, 1953, p. 352). For example, the metabentonites of Ordovician age described by Weaver and Bates (1952, pp. 258–261) are composed of illite and considered to have been montmorillonite originally. The present writer is not acquainted with the diagenetic alteration of illite to montmorillonite in other sedimentary rocks.

Original Deposition

Original deposition as a possible mode of origin is favored primarily by theoretical

evidence. As Grim (1953, pp. 356–357) points out, parts of the geologic column are characterized by an abundance of montmorillonite and other parts contain almost none. For example, at the present time, a relative abundance of montmorillonite is being carried to the sea (Grim and Johns, 1954, pp. 91–95). If the montmorillonite in question were the result of original deposition, it might have formed either authigenically in the deeper water (by the adsorption of sodium or calcium cations on skeletal silica-alumina structures) or have been formed in the weathering process and selectively transported to the deeper water.

According to present knowledge, the formation of montmorillonite is favored by basic conditions. The abundance of carbonaceous matter in the Phosphoria shales and mudstones indicates reducing bottom conditions, probably with a corresponding low pH (Rooney, 1956a, p. 2268). Even if the bottom of the Phosphoria Sea were an acidic environment, the upper part of the sea may have been basic, favoring the formation of montmorillonite. The acidic bottom conditions and the related low solubility of silica theoretically would favor the formation of authigenic kaolinite and/or preserve the kaolinite transported there from land (cf. Mason, 1952, p. 142). However, for the upper part of the sea to have favored the formation of montmorillonite and the lower to have favored kaolinite seems a rather improbable relationship. If either of the two minerals is the result of original deposition following authigenesis or weathering, the given facts indicate that kaolinite is the more likely of the two.

Montmorillonite generally is regarded as occurring in a finer particle size than the other clay minerals. If such is the case, montmorillonite may have been mechanically separated from the larger clay minerals by longer transportation and slower settling. The data obtained by the writer regarding the relative distribution of the clay minerals in the size fractions are both scattered and inconclusive and therefore not itemized here. They show with certainty only that kaolinite occurs in larger particles than illite or montmorillonite.

Volcanic Activity

Volcanic activity, whether with a concurrent or subsequent deposition of volcanic ash in the Phosphoria Sea, is a possible mode of origin. During the middle part of Permian time, there was volcanic activity in eastern California, western Nevada and along the Idaho-Oregon boundary; however, there is no known occurrence of Permian volcanic deposits in Montana. Fluorine, a common constituent of volcanic exhalations, is enriched in the Phosphoria formation; however, it is associated not only with the Mount Fleecer and adjoining areas but with the entire phosphate field. Thus far montmorillonite has been found in only three restricted areas and there throughout most of a sequence 25 feet thick. Because volcanic ash generally occurs as widespread thin beds, such an origin does not seem likely here. The tranquil conditions under which the Phosphoria mudstones were deposited minimize the possibility of reworking by currents. Although it must be admitted the extremely carbonaceous nature of the mudstones renders their petrographic study unrewarding, this method revealed no evidence of volcanic material.

Hydrothermal Alteration

A hydrothermal origin of montmorillonite and kaolinite is favored by the following evidence: (1) proximity of intrusions, (2) metamorphism of overlying and underlying beds, (3) metamorphism within the Phosphoria, (4) quartz and calcite veins, (5) presence of talc.

1.—Proximity of intrusions. In each of the areas sampled, the Phosphoria Formation has been intruded by igneous rocks; in fact, the sections sampled in the Highland Mountains and on Mount Fleecer contain sills. Furthermore the Mount Fleecer area is a roof pendant on a stock probably related to the Boulder Batholith (Moore, 1956).

2.—Metamorphism of overlying and underlying beds. The dolomite of the Franson Member of the Park City Formation underlying the Phosphoria Formation has been marmorized in the Mount Fleecer and Highland Mountains areas and partly silicified and altered to talc in the Quartz Hill area. The overlying Shedhorn Sandstone has been recrystallized in the Highland Mountains area.

3.—Metamorphism within the Phos-

phoria. Lowell (1955) has noted metamorphism in the same area, but his study was devoted primarily to the rocks immediately adjacent to the intrusives and he did not run X-ray analyses of the clays. He found that the Mount Fleecer rocks were the most noticeably altered. At the contact with the sill, the dark-colored mudstones had been bleached, collophane had altered to apatite, the ovulitic texture had been partly destroyed, and migration of quartz and phosphatic material had occurred. In the Highland Mountains section the present writer found hornfels largely constituted of recrystallized muscovite and quartz.

4.—Quartz and calcite veins. A fine network of fractures filled by quartz and calcite veins, generally about 1 mm in diameter, in most of the Mount Fleecer mudstones suggests hydrothermal alteration. The veins prove that fluids did move through the otherwise rather impermeable formation.

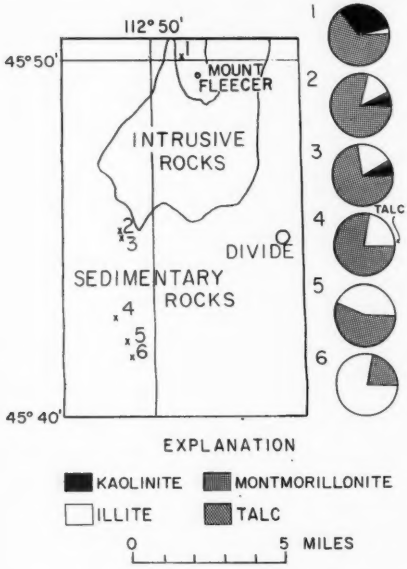

FIG. 4—Map showing distribution of montmorillonite, kaolinite, illite and talc (calculated as the product of thickness of each unit and intensity of basal reflection of each mineral) in six stratigraphic sections of the Retort Phosphatic Shale Member of the Phosphoria Formation in southwestern Montana.

5.—Presence of talc. X-ray patterns reveal talc in eight samples of the Quartz Hill and Trusty Lake sections (fig. 2).

Fowler (1955, p. 62) also noted the presence of talc in one sample of Quartz Hill section C and suggested that hydrothermal solutions may have been introduced along a minor fault. The present writer also believes that talc is due to the migration of magnesium-bearing fluids along local channels of easy access or from the hydrothermal alteration of local carbonate lenses.

DISCUSSION

Of the five possible modes of origin of montmorillonite and kaolinite described above, hydrothermal alteration of Phosphoria mudstones seems to accord best with the evidence.

The clay mineral suite in the Trusty Lake sections located farthest from the Boulder Batholith and not associated with thick sills or adjacent stocks is similar to that found by Herr in the Phosphoria Formation over much of southwestern Montana. As would be expected in a marine shale, illite is the dominant clay mineral. Toward the north and toward the area most affected by intrusions the illite content decreases almost to absence in the Mount Fleecer section (fig. 4). Kaolinite, on the other hand, is a major constituent of the samples collected near the batholith but is almost absent in the Trusty Lake samples. Going south from the batholith, montmorillonite is associated with kaolinite in the Mount Fleecer samples, with both illite and kaolinite in the Quartz Hill samples and with illite in the Trusty Lake samples (fig. 4). Although its distribution seems to be controlled by local factors, talc is found only in samples high in montmorillonite.

The following sequence of events seems a coherent explanation for the mode of occurrence and the distribution of the clay minerals in the Mount Fleecer, Quartz Hill, Trusty Lake and Highland Mountains areas. The dominant clay mineral either deposited or formed during diagenesis in the Phosphoria Sea was illite. *Possibly* kaolinite was deposited as a detrital mineral or formed authigenically in areas of very restricted circulation such as the Mount Fleecer area. During the emplacement of the Boulder Batholith and numerous associated sills and

stocks, hydrothermal solutions altered the illite to montmorillonite and possibly the montmorillonite to kaolinite. The formation of talc was controlled by local carbonate lenses or by channels of easy access such as bedding-fault planes.

SUMMARY

Several measured sections in the Phosphoria Formation of southwestern Montana contain, throughout a thickness of more than 20 feet, an unusual abundance of montmorillonite, locally associated with kaolinite or talc. The mineral association, proximity to igneous intrusions, associated hydrothermal activity, and metamorphism indicate that the unusual abundance of montmorillonite is primarily the result of hydrothermal alteration of pre-existing clay minerals, probably illite and mixed-layer illite-montmorillonite. Such widespread hydrothermal alteration of an argillaceous formation more than 20 feet thick and the formation of a mineral suite montmorillonite-kaolinite-illite or montmorillonite-talc-illite is perhaps unique.

ACKNOWLEDGMENTS

The writer thanks W. R. Lowell and H. H. Murray of Indiana University, who advised the writer in his field and laboratory investigations respectively and who critized the manuscript. Victor Chemical Company kindly permitted the use of samples collected by W. R. Lowell, S. Theodosis, W. E. Fowler and G. T. Moore through several field seasons. Special thanks are due to G. T. Moore for his laboratory assistance.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 4, PP. 460–468
FIGS. 1–6, DECEMBER, 1957

SIZE ANALYSIS OF SAND BY A SEDIMENTATION TECHNIQUE[1]

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ABSTRACT

The particle size distributions of sand-size material can be determined either directly by microscopic measurement, or indirectly by sieving or by sedimentation techniques. Routine size analyses by microscopic measurements are impractical because they are too time consuming, although other properties such as grain shape or roundness can be determined when making size analyses by this method. Sieve analyses, because of their convenience and resulting fractionation, have been most extensively used to determine the size frequency distribution of sands. However, since most sediments are deposited in fluid media, sedimentation size analyses are often desirable because they most nearly approach the hydrodynamic conditions of deposition. This paper discusses a sedimentation technique employed for the analysis of sand-size material, and demonstrates, by means of experiments with glass spheres, that single grain terminal settling velocities can be used as suitable approximations for fall rates of grain groups. The settling velocities for groups of grains are 10 to 15 percent faster than those for single grains of the same diameter. Comparative results of size analyses of the same sample indicate that sedimentation diameters generally were coarser than sieve diameters but finer than microscopically measured diameters.

INTRODUCTION

The Emery settling tube (Emery, 1938), which utilizes the principle of terminal settling velocities, is used at the Scripps Institution of Oceanography's sedimentation laboratory for the routine size analysis of "sand."[2] The simple method employed is rapid, and has a reproducibility which compares favorably with that of sieving (Poole, et al., 1951). Since it is a sedimentation method of size analysis, the settling tube technique more nearly approaches natural conditions of deposition and results in a better approximation of sediment particle behavior than either sieve or microscopic size analyses. The settling tube has been modified recently by the author (fig. 1) with the addition of a device[3] which makes the introduction of the sample more uniform.

The terminal fall velocities for sand-size materials have been determined experimentally (among others, Heywood, 1938; U. S. Engineers 1941, 1943) for single spherical grains. The use of single spheres in these experiments obviously simplifies theoretical and experimental considerations in determining fall velocities. However, the fact that the natural sand particles seldom approach a spherical shape led to the concept of the "sedimentation radius" defined by Wadell (1934) as "the radius of a sphere of the same specific gravity and of the same terminal uniform settling velocity as a given particle in the same sedimentation fluid." This definition presents a practical solution to the problem of expressing the "size" (radius or diameter) of particles which occur in nature. If, for the sake of convenience, the density of quartz is used as a reference, this definition serves adequately for expressing size in terms of a standard and is equivalent to the "hydraulic value" defined by Schöne (cited by Krumbein and Pettijohn, 1938, p. 94) as the diameter of a quartz sphere having the same settling velocity as a given particle in water. Moreover, since it is impractical to perform a routine sedimentation size analysis by dropping particles one at a time through a column of water to determine their settling velocities (hence size), many particles must be dropped. In such a case the settling velocities determined for single grains do not apply exactly. In a

[1] Contribution from the Scripps Institution of Oceanography, New Series No. 957. This investigation was supported by a grant from the American Petroleum Institute, Project 51. Manuscript received April 8, 1957.

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[2] The term "sand" as used in this paper includes all particles with diameters between 1.0 mm and 0.0625 mm. This includes all the Wentworth sand size grades except very coarse sand (2.0 to 1.0 mm).

[3] This device was made by George S. Bien and is similar to the double cone device of Puri (1934).

settling tube analysis the grains fall as a group, and the grains have a higher initial settling velocity than they should because of the introduction of the sample as a unit.[4] In order to determine the effect that the introduction of the sample as a unit has on the settling velocities of particles, a series of tests were made using glass spheres. These were chosen because they were spherical, easy to obtain, and should give the same diameter whether measured by sieves, microscope, or sedimentation (using settling velocities for spheres with the density of glass).

The second part of this study consisted of making size analyses of four natural sands and a sample of glass spheres (with a "controlled" size distribution) by these three methods for the purpose of comparison.

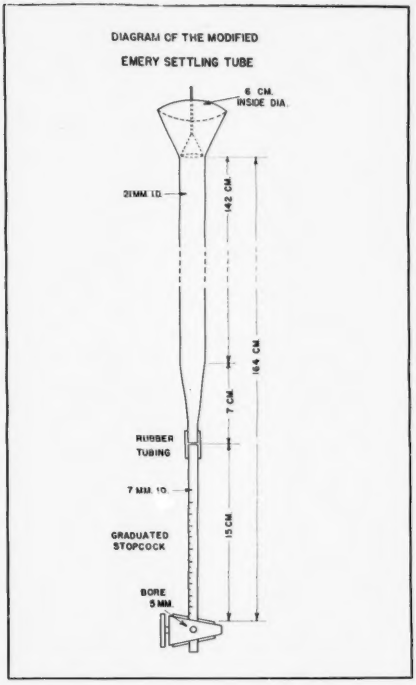

FIG. 1.—Diagram of the modified Emery settling tube showing the double-cone device for introducing the sample into the settling tube

[4] Emery's (1938) settling velocities were determined by the time of fall of sands sieved into Wentworth size grades, and are, therefore, closely related to sieve diameters rather than to sedimentation diameters.

METHODS OF STUDY

Only an outline of the methods used in preparing the glass spheres for the sedimentation tests will be given here, since complete details of the procedures followed can be found in U. S. Engineers Report #10, 1953. Irregularly shaped grains were eliminated by first sieving each size grade with a Ro-tap shaker, re-sieving lightly by hand, and assuming the material retained after hand sieving to be irregular in shape and discarding it. For large sizes, coarser than 1.50ϕ (0.351 mm), irregularly shaped grains were eliminated by rolling the grains down a narrow, inclined plate. The size distribution of each sieve fraction was determined by microscopically measuring the diameters of a random sample of 400 grains from each size grade. New Tyler Standard Screen Scale sieves with intervals based on the $\sqrt[4]{2}$ grade scale were used for the sieve analyses in this study. These sieves were calibrated by microscopically measured glass beads, and the difference between the mean diameters,

$$\left(\frac{\text{Coarser nominal sieve opening} + \text{finer nominal sieve opening}}{2}\right),$$

based on the nominal sieve openings[5] of each size fraction was generally slightly finer than the mean diameters based on measured glass spheres. From these microscopic measurements, percentages of grains larger and smaller than the nominal sieve openings were found, and the "controlled" size distribution of the sedimentation test samples could be obtained. The density of the beads in several size fractions was determined using distilled water and carbon tetrachloride in 25 ml pycnometers and 100 ml volumetric flasks. Densities of the larger beads averaged 2.47 gm/cc and were quite constant, but in the sizes finer than 3.25ϕ (0.105 mm) were much more variable. It was necessary to use

[5] The nominal opening is the rated sieve opening, and the effective opening may be defined as the mean size of the grains that will pass through a sieve and be retained on the next smaller size sieve. These grain sizes are determined by the microscopic measurement of the intermediate diameters.

heavy liquids to obtain grains with a uniform density (2.32 gm/cc) for use in determinations of the terminal fall velocity of single grains. The final step of preparation was to check the settling velocity of individual glass spheres from these samples of known size. This was done by dropping the grains down the settling tube, in distilled water held at a temperature of 24° C, and timing them during a measured distance of fall. The ratio of the largest particle diameter to the tube diameter was about 0.02 which eliminated any serious wall effects (McNown, et al , 1948). The settling velocities so determined were plotted against diameter on log-log paper and a smooth curve drawn. To render these data more useful for sedimentation studies, the curve was then transformed in the usual manner, by the use of Reynolds number R_e, and the coefficient of resistance, C_r (Krumbein and Pettijohn, 1938, p. 104), to one (fig. 2) for spheres with a density of quartz, 2.65 gm/cc. This resulting curve is almost identical with the curve shown for quartz spheres settling in distilled water at 25° C in the U. S. Engi-

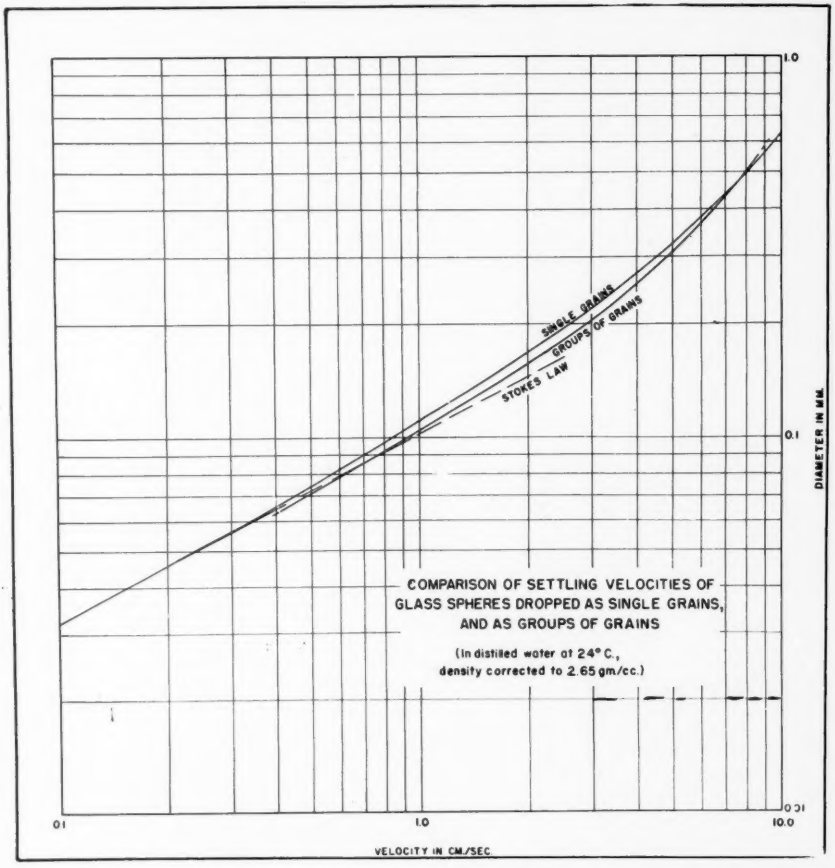

FIG. 2.—Comparison of settling velocities of single glass spheres and groups of glass spheres. The curves originally determined using glass spheres were transformed to curves for spheres with the density of quartz.

TABLE 1.—*Times for quartz spheres to fall 164 cm in distilled water at various temperatures (°C). From settling velocities determined by Heywood's (1938) method*

Diameters in		Settling times (Min.-sec.)					
ϕ	mm	18°	20°	22°	24°	26°	28°
0.00	1.000	11	10	10	10	10	10
0.50	0.71	15	15	15	14	14	14
0.75	0.59	18	18	18	17	17	17
1.00	0.50	22	21	21	21	20	20
1.25	0.42	27	26	26	25	25	24
1.50	0.354	32	32	31	30	30	29
1.75	0.297	40	39	37	37	36	35
2.00	0.250	49	48	47	46	45	44
2.25	0.210	1 03	1 01	1 00	58	56	54
2.50	0.177	1 23	1 20	1 17	1 15	1 12	1 10
2.75	0.149	1 51	1 46	1 41	1 37	1 34	1 31
3.00	0.125	2 28	2 23	2 17	2 11	2 06	2 02
3.25	0.105	3 21	3 13	3 04	2 56	2 50	2 44
3.50	0.088	4 34	4 23	4 11	4 03	3 52	3 45
3.75	0.074	6 16	6 00	5 45	5 31	5 20	5 08
4.00	0.0625	8 40	8 15	7 53	7 31	7 09	6 53
4.25	0.053	11 47	11 18	10 43	10 17	9 52	9 27
4.50	0.044	16 59	16 10	15 16	14 37	14 01	13 36

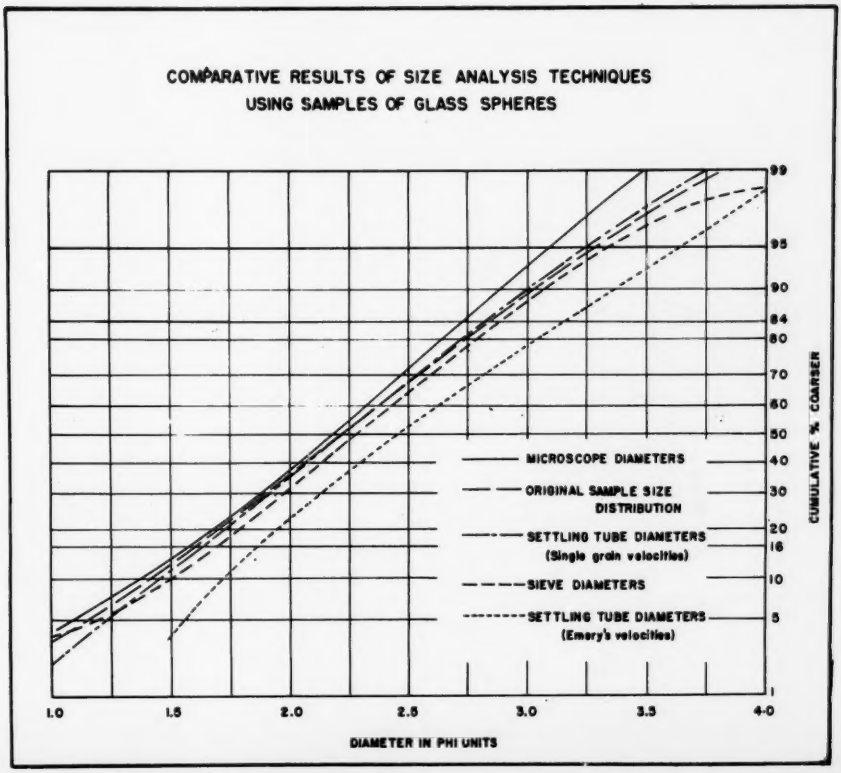

FIG. 3.—Comparison of several methods of size analysis of samples of glass spheres with a controlled size distribution. Settling velocities for the settling tube analyses were determined for spheres with the density of glass.

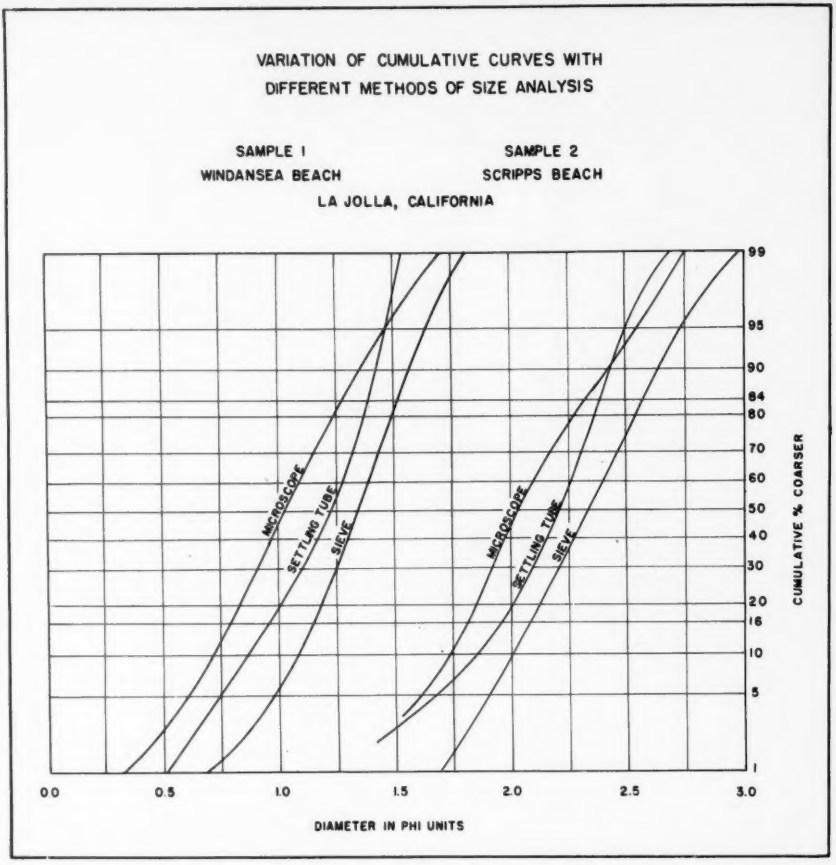

FIG. 4.—Comparison of cumulative curves of samples showing differences owing to the method used for size analysis. Settling times determined by Heywood's method used for settling tube analyses. Diameters measured by microscope were converted to weight to make them comparable to sieve analyses.

neers Report #7, 1943, and extends smoothly into the Stokes' law curve.

To determine the effect on settling velocities caused by the introduction of the sample, using Puri's (1934) device, and fall of a group of grains in the settling tube, tests were run using samples of the glass spheres with controlled size distributions. Settling velocities were determined indirectly by a method similar to that of Emery (1938). The sample was dropped once to determine the total cumulative height in the graduated part of the tube, and from the known size distribution the cumulative height of each size fraction was noted on the graduations. The sample was dropped again and the time to reach each of the various cumulative heights was recorded and settling velocities calculated. Three test samples of 3.50 grams each were run in duplicate to avoid gross errors. Two of these samples contained between 40 and 60 percent material coarser than 2.0ϕ (0.246 mm) while the other contained about 70 percent material between 3.0ϕ (0.124 mm) and 4.0ϕ (0.061 mm). The settling velocities determined by

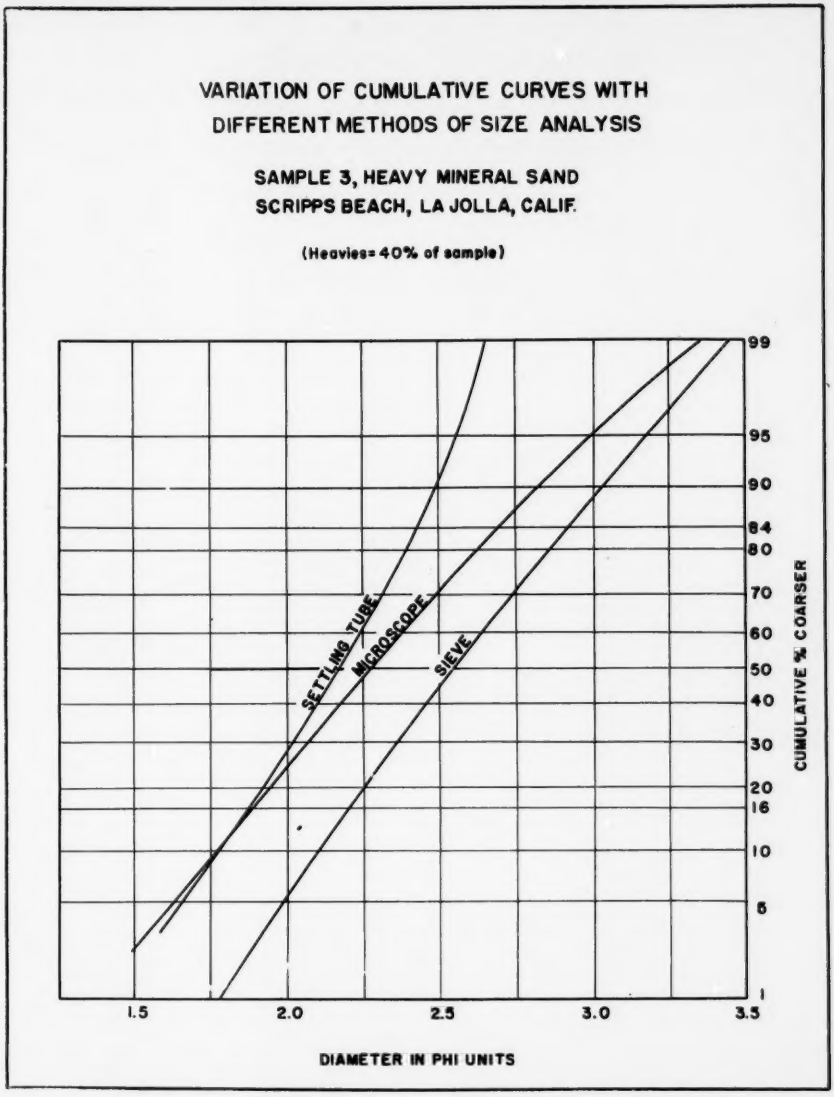

FIG. 5.—Comparison of cumulative curves of samples showing differences owing to the methods used for size analysis. Settling times determined by Heywood's method used for settling tube analyses. Diameters measured by microscope were converted to weight to make them comparable to sieve analyses.

group-grain tests were plotted against diameter and this curve was transformed, in the same manner as that for single grains, to one for spheres with a density of 2.65 gm/cc. It is apparent that the single grains fall about 10 to 15 percent more slowly than the group-dropped grains of the same diameter (fig. 2). Hence, the use of settling

velocities based on the fall of single grains results in diameters about ½ϕ unit coarser than the known diameters. The above is true only for the sample weight used, in this case 3.50 grams. McNown and Lin (1952), using homogeneous concentrations of uniformly sized material, have shown that large sample concentrations significantly reduced fall velocities. However, the effects of sample concentration on settling velocities for other than uniform and homogeneous (i.e., all particles of the same settling velocity distributed homogeneously through the column) samples are not known. In this study the effect on settling velocity of only three groups of samples with different particle size distributions, each weighing 3.50 grams, was evaluated. Therefore, because of unknown effects of concentration, it appears best to use settling velocities of single grains for routine size analyses, always remembering that the diameters obtained are probably somewhat larger (about ½ϕ or less) than the actual diameters. Table 1 gives times of fall (for 164 cm—the length of the Emery settling tube) for quartz spheres in distilled water at various temperatures, using settling velocities determined by Heywood's (1938) method. These times of fall are useful for making up a settling tube data sheet, and were used in the settling tube analyses of the natural sands.

Size analyses of four sand samples (and a

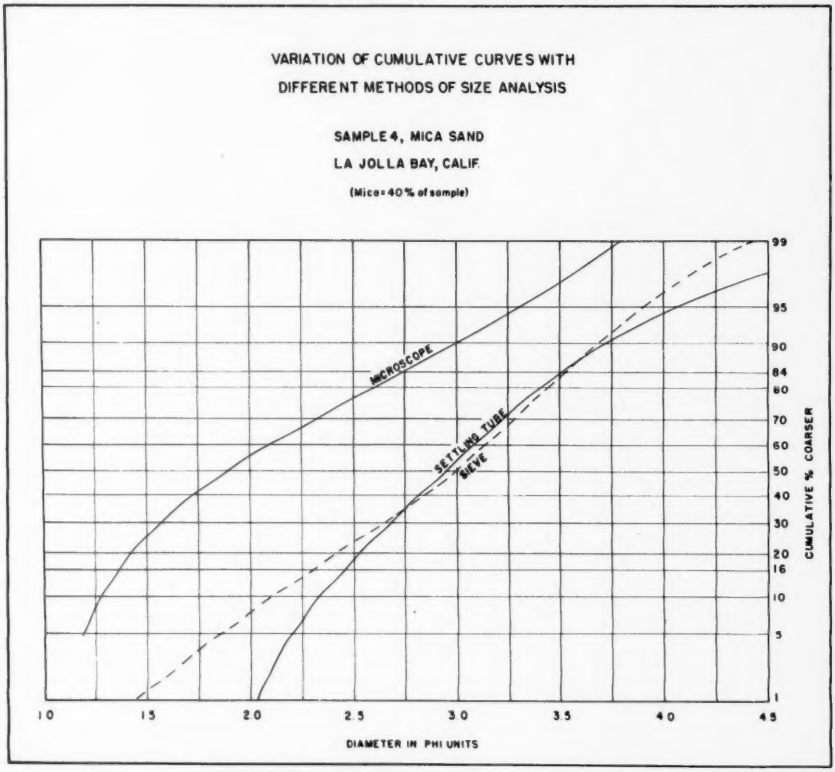

FIG. 6.—Comparison of cumulative curves of samples showing differences owing to the methods used for size analysis. Settling times determined by Heywood's method used for settling tube analyses. Diameters measured by microscope were converted to weight to make them comparable to sieve analyses.

TABLE 2.—*Summary of advantages and disadvantages of three methods of size analysis*

Method	Advantages	Disadvantages
Microscope	Factors such as shape and roundness can be measured while making size analysis. Size data expressed as a number frequency	Tedious and time consuming. Size distribution must be converted to weight to make it comparable to other methods, and this is shown to be inadequate
Settling Tube	Rapid and easy to use. Shape, volume, and density of particle are taken into account. May approach actual conditions of deposition	Sample on introduction tends to fall as a unit giving slightly erroneous settling velocities. Volume measurements rather than weight used
Sieve	Easy to use. Reliable. Most size analyses of sand-size material have been made by this method	Results adversely affected by particle shape. Density not taken into account. Rated sieve opening smaller than effective openings and change with usage

glass sphere sample with a controlled size distribution) were made by sieving, sedimentation, and microscope. Two of the samples were well-sorted sands with median diameters ranging from about 1.25ϕ (0.420 mm) to 2.25ϕ (0.210 mm), the third a sand with about 40 percent (by weight) heavy minerals (containing about 60 percent hornblende), and the fourth a sand with about 40 percent (by weight) mica. These samples were treated with 3 N HCl to free them from carbonates such as shell fragments, then were washed, soaked in a dispersing agent (0.025 N sodium hexametaphosphate, $Na_6(PO_3)_6(?)$), and stirred for 10 minutes in a malt-mixer. Any material finer than coarse silt (0.03125 mm) was decanted and the coarse material dried and saved. The dried portions were divided (by using the Otto microsplit) into fractions for the settling tube, sieve, and microscopic size analyses. A sample of glass spheres was made up with a controlled size distribution and was split into fractions for the three methods of size analysis.

The microscope size analyses were made by measuring the intermediate diameters, which were converted to weight in order to make them more comparable to sieve analyses (Krumbein and Pettijohn, 1938, p. 302). The microscopic size analyses were prepared by carefully splitting a sample to 300 or 400 grains, sprinkling them on a glass slide and then tapping the slide a few times so the grains would assume their most stable position. The most stable position is one in which the grains tend to lie on one of their larger surfaces, more or less parallel to the plane containing the largest and intermediate diameters (Wadell, 1935; Pettijohn and Ludahl, 1943). Only 300 to 400 grains were measured (using a micrometer eyepiece) according to the "rule of thumb" of Krumbein and Pettijohn (1938, p. 178), i.e., grains were measured until there was no great change in the size distribution.

RESULTS AND CONCLUSIONS

Results of the different methods of size analysis for a sample of glass spheres with a controlled size distribution are shown in figure 3. The microscope, settling tube (using single grain fall velocities), and sieve analyses fall close to the original (controlled) size distribution, while the settling tube analysis using Emery's velocities (corrected for the density of glass beads) gives a much finer distribution. This comparison shows that any of these methods of analysis are adequate to determine size distributions of spherical particles, but this is not true for natural sands where spherical shapes are rare.

The settling tube analyses, using fall velocities determined by Heywood's (1938) method, consistently gave coarser median diameters (about $\frac{1}{8}\phi$ coarser) than the sieve analyses in all the samples of natural sand (figs. 4–6). The greatest variation in median diameters occurred in the sand rich in heavy minerals. The heavies, which made up most of the finer fraction of the sand, settled with quartz grains of larger diameter and thus gave a much larger median diameter (about 0.5ϕ coarser) than the sieve analysis. In the mica-sand analyses the sieve and settling tube median diameters were similar but the tails of the distributions were quite different.

The mica grains which were in the coarsest fraction of the sample settled with finer quartz grains. The difference between settling tube and sieve diameters in these natural sands can be partially explained by the fact that effective diameters of the sieve are larger than the nominal diameters. Moreover, sieves give a size distribution dominated by particle shape (density is not a factor), whereas in a sedimentation analysis the shape, volume, and density of the grains determine their settling velocities and related size. Corrections of settling velocities for various particle shapes were attempted (Heywood, 1938), but the amount of labor involved and the inconsistencies of the results were too great to make them useful for routine size analyses. Consequently it was decided to use sedimentation diameters only as an expression of size.

In all except the heavy mineral sample, the median (intermediate) diameters determined by the microscope method were coarser than those of either the sieve or settling tube. In the microscopic size analyses shape is also dominant. If the grains were nearly all equi-dimensional (more like spheres), measurements of the intermediate diameters, converted to weight, would agree more closely with sieve and sedimentation analyses than if the grains were lath-shaped or disk-shaped.

From this study it is concluded that single grain settling velocities are most useful for settling tube analyses and until the effects of concentration and the introduction of the sample on settling velocities are adequately understood, the indiscriminate use of correction factors unnecessarily complicates results and reduces reproducibility among analysts. The advantages and disadvantages of the various methods of size analysis used here are summarized in table 2.

ACKNOWLEDGMENTS

The writer wishes to express his appreciation to G. A. Rusnak for his many valuable suggestions and critical reading of the manuscript. He would also like to thank F. P. Shepard, D. L. Inman, and J. R. Curray for their helpful suggestions and careful reading of the manuscript.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 4, PP. 469–470
DECEMBER, 1957

DISCUSSION

RELATIONS OF GYPSUM AND ANHYDRITE

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In the June issue of this Journal some objections are raised by Mr. M. I. Goldman (1957) to an article of mine in the March issue of the same Journal (Ogniben, 1957a). Due reply is given here.

Regenerated anhydrite

1) My final report has been published (Ogniben, 1957b), and there epigenic anhydrite on primary gypsum is illustrated (figs. 79–80–81–85–86–87–88–89), identical with epigenic anhydrite on secondary gypsum (figs. 82–83–84–90).

2) My anhydrite "lamellar or acicular in habit, often oblique to the optical axes" (Ogniben, 1957a, p. 67, column 2, last paragraph) has nothing to do with low birefringence (Goldman, 1957, p. 196, column 1, penultimate paragraph). Just the habit is often oblique to optical axes, being often ruled by domal faces, characteristic of epigenic anhydrite, instead of pinacoidal faces only as is the case in primary anhydrite. All possible birefringence values can be observed, only depending upon orientation of the single crystal in the thin section. No preferred orientation has been observed in epigenic anhydrite, nor is any particular anhydrite species of "low birefringence" known thus far.

Integration

1) The word "integration" could have been used for the German word "Sammelkristallisation." But the "integration" phenomena described by Goldman (1952) never could re-enter in "Sammelkristallisation" as defined commonly in the literature and reported by me (Ogniben, 1957a, p. 77, column 1). Moreover, a definition of "integration" as something different from his own descriptions has not been given by Goldman. Therefore, the use of "integration" for "Sammelkristallisation" must be avoided, and in its place I proposed "syncrystallization."

2) Large secondary gypsum crystals have been interpreted by me as a first stage in anhydrite-gypsum transformation, and the surrounding fine-grained aggregate as a last stage, because of the ruptural derivation of the aggregate from the large crystals, as it can be seen in my figures 5 and 6 (Ogniben, 1957a). Large gypsum crystals with irregularly and continuously varying optical orientation have been termed "superindividuals" (a word familiar to petrofabric students), and explained with deformation by volume increase in transformation under pressure. They correspond to an intermediate zone, therefore to an intermediate stage, between large normal crystals and fine-grained aggregates, as it can also be seen in the same figures 5 and 6.

Large normal crystals and superindividuals are both characterized by residual anhydrite microliths, as I emphasized in my article (Ogniben, 1957a, p. 76, last paragraph of column 1 up to column 2), contrarily to the surrounding fine-grained aggregate, which is anhydrite-free and demonstrates, therefore, a more advanced and successive stage in anhydrite-gypsum transformation.

In Sicily, as pointed out in my article, some beds are made up by selenite cores surrounded by superindividual zones grading into fine-grained aggregate, while other beds are made up by superindividual cores grading into fine-grained aggregate. According to evidence of ruptural character of the superindividual polarization, I explained the second structural type as due to transformation under external pressure, whereas the selenitic structural type should have been formed under little or no external pressure.

Goldman (1952) did not find the selenitic type of gypsum in his cap rock, but only superindividuals and fine-grained aggregates, to which he now raises objection (Goldman, 1957, p. 196, column 2). This is just what had to be expected in cap rock,

where gypsum most certainly formed from anhydrite under external pressure.

3) The vein-like patches in figures 10 and 11 of my article contain residual anhydrite microliths, while the fine-grained gypsum in the same figures does not, as I repeatedly pointed out (Ogniben, 1957a, p. 74, column 1, also explanation of fig. 11). Thus, the fine-grained aggregates must be regarded as the above-mentioned more advanced and successive stage of transformation from anhydrite, and the vein-like patches as the less advanced one. This must lead, in spite of the first appearance, to consider as shear zones the fine-grained aggregates, and not the vein-like patches. Being limited by exceedingly well-developed shear zones, the latter probably acquired a similar pattern, as "negative" shear zones.

4) The diapiric uplifts in my article (Ogniben, 1957a, p. 66, column 1) do not touch upon the fabric of the evaporites, but only of older clayey formations in anticlinal cores.

5) The absence of "Sammelkristallisation" evidence did not appear as a problem to me. "Sammelkristallisation," or "syn-crystallization," should take place in metamorphism or in protracted diagenesis, that is, under tectonic or load pressure and/or temperature. This could rarely be the case with gypsum, since it must transform in anhydrite under moderate pressure (with escape of water) and temperature. The only "Sammelkristallisation" observed by me is limited to the crystalloblastic shapes of the fine-grained gypsum, in the moderate amount which is always to be expected in near-surface phenomena with such a mobile substance as gypsum.

No stages of grading from fine-grained aggregates to large clear gypsum crystals were observed, for the simple reason that this process did not take place in Sicilian Upper Miocene gypsum. Only the opposite process occurred, as is illustrated especially by my figures 5 and 6 (Ogniben, 1957a). The large selenite crystals grew directly from anhydrite under little or no pressure.

6) It is not necessary to see transformation "actually take place" (Goldman, 1957, p. 197, column 2). Residual anhydrite in gypsum is sufficient evidence of transformation. Where residual anhydrite is absent, transformation must have advanced to a more complete stage, or it must never have taken place.

7) The calcium sulphate deposition took place in Paleozoic time in American evaporites of the salt domes, and in Upper Miocene time in Sicily. What we now observe is the result of many mineralogical and structural transformations, which should be much easier to be retraced to original conditions in the less stressed Upper Miocene rocks, than in the older and severely stressed Paleozoic ones.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 4, PP. 471–475
DECEMBER, 1957

SOCIETY RECORDS AND ACTIVITIES

REVISED CONSTITUTION AND BY-LAWS

(APPROVED, 1956 AND 1957)

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS
A DIVISION OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

CONSTITUTION

ARTICLE I. NAME

The Society shall be known as the Society of Economic Paleontologists and Mineralogists.

ARTICLE II. OBJECT

The object of the Society shall be to promote the science of stratigraphy through research in paleontology and sedimentary petrology, especially as these relate to development of knowledge of the geology of petroleum.

ARTICLE III. MEMBERSHIP

1. The Society shall be composed of active members, associate members, honorary members, correspondents, and patrons.

2. Active members shall be persons engaged in paleontologic, petrographic, or stratigraphic studies as applied to the geology of petroleum and who have been duly elected active members, juniors, or associates in The American Association of Petroleum Geologists.

Active and honorary members only shall be known as members.

3. Associate members shall be known as associates. Any person engaged in paleontologic, petrologic, or stratigraphic studies that have application to the geology of petroleum is eligible for associate membership. Associates shall enjoy all the privileges of membership in the Society, save that they shall not hold office, sign applications for membership, or vote.

4. Honorary members shall be persons of distinguished achievement whose contributions to paleontology, petrology, and stratigraphy have an application to the geology of petroleum.

5. Correspondents shall be persons not resident in North America who have made distinctive contributions to paleontology, petrology, and stratigraphy that have application to the geology of petroleum.

6. Patrons shall be persons who have bestowed important favors on the Society.

ARTICLE IV. OFFICERS

1. Executive authority of the Society is vested in a council consisting of six members, duly elected officers, as follows: president, vice-president, secretary-treasurer, the past-president, and the editor of each of the two Journals. The chairman and the vice-chairman of the Research Committee and the presidents of Regional Sections shall be non-voting members of the council.

2. The president shall discharge the usual duties of a presiding officer at all meetings of the Society and council.

3. The vice-president shall assume the duties of the president in case of his absence.

In the event of the absence from the meetings of both president and vice-president, the duties of presiding officer shall fall upon one of the other members of the council in the following order: past-president, secretary-treasurer.

4. The secretary-treasurer shall keep records of the proceedings of the Society, and a complete list of the membership. He shall attend to the preparation and mailing of notices and other materials required in the business of the Society. The secretary-treasurer shall have custody of all funds of the Society, and shall keep a detailed account of receipts and disbursements.

5. The council shall consider all nominations for membership and pass on the qualifications of the applicants; may elect honorary members, correspondents, and patrons; shall have control and management of the affairs and funds of the Society; shall determine the manner of publication and pass on the material presented for publication; and shall designate the place of the annual meeting. It is empowered to establish a business headquarters for the Society and to employ such persons as are needed to conduct the business of the Society.

6. Elections shall be held annually to

select a president, vice-president, secretary-treasurer, and the editors.

ARTICLE V. MEETINGS

1. The Society shall hold at least one stated meeting a year, which shall be designated as the annual meeting. The time and place of the annual meeting shall be designated by the council, but in general, it shall be held in connection with the annual meeting of The American Association of Petroleum Geologists.

2. The annual meeting shall be devoted to the reading and discussion of scientific papers, to the transaction of Society business, and other appropriate functions.

3. The program for the annual meeting shall be arranged by the council, or under its direction.

ARTICLE VI. SECTIONS

Local sections of the Society may be established according to provisions of the by-laws.

ARTICLE VII. AMENDMENTS

The constitution may be amended by a two-thirds vote of returned mail ballots received by the secretary-treasurer sixty days after proposal of amendments with provision for vote is mailed to the membership; provided that the proposed amendment has been signed by at least twenty members, and provided further that the proposed amendment must first have the approval of the council and the executive committee of The American Association of Petroleum Geologists.

BY-LAWS

ARTICLE I. DUES

1. The fiscal year of the Society shall correspond with the calendar year.

2. The annual dues of members and associates of the Society who desire only the *Journal of Paleontology* shall be ten dollars ($10.00). The annual dues of members and associates who desire only the *Journal of Sedimentary Petrology* shall be seven dollars ($7.00). Members and associates may receive both Journals by the payment of seventeen dollars ($17.00). Members of the society who are also members of the Paleontological Society and receive the *Journal of Paleontology* through the latter Society, may retain membership in the Society of Economic Paleontologists and Mineralogists by the payment of two dollars ($2.00) per year dues. The annual dues are payable in advance on the first day of each calendar year. A bill shall be mailed to each member and associate before September 1 of each year, stating the amount of annual dues and the penalty and conditions for default of payment. Members and associates who shall fail to pay their annual dues by January 1 shall not receive further copies of either Journal, nor shall they be privileged to buy Society publications at special discounts made to the membership, until such arrears are met.

3. The council may from time to time elect as honorary members, correspondents, and patrons, candidates who have been nominated by a majority vote of the research committee. A vote of four members of the council shall be required for election. Honorary members, correspondents, and patrons shall not be required to pay annual dues.

ARTICLE II. DUTIES AND PRIVILEGES OF MEMBERS

1. Members and associate members dropped for non-payment of dues may apply to the council for reinstatement, and, provided settlement is made of any outstanding indebtedness for publications and other charges approved by the council, may be reinstated by vote of four members of the council.

2. Members shall be eligible to receive publications of the Society at special subscription rates as authorized by the council or as provided in these by-laws.

3. The council is authorized to transmit without charge such publications as it may direct to honorary members, correspondents, and patrons.

4. Only active and honorary members shall have the right to vote in electing officers and in transacting the business of the Society.

ARTICLE III. OFFICERS

1. Nominations for officers shall be made in the following manner. Prior to September

1 of each year, the president shall designate two nominating committees, instructing each committee to submit nominations for president, vice-president, secretary-treasurer, and editors, these nominations to be in the secretary's hand before September 15. If desired, the same persons may be nominated by the two committees for the offices of secretary-treasurer and editor of each Journal, respectively, but nominations for president and vice-president shall not include the name of the same person on the two slates. The nominations of the first committee to file its report will have precedence in case of overlapping nominations and the other committee shall then be requested to change its nominations.

2. Ballots containing the nominations for officers, alphabetically arranged under each office, shall be prepared by the secretary-treasurer and mailed to each member of the Society on or before October 1. Neither the ballot nor the enclosing envelope need contain the name of the voting member, but an outer envelope that contains the sealed ballot must bear the name of the voting member. The returned ballots received by the secretary-treasurer on or before December 1 shall be counted by him, and if requested, shall be submitted to recount by the council. A plurality of the votes received for any office constitutes election.

3. If, after his election by the regular ballot, the president shall not be able to discharge the duties of his office, because of death or resignation, the duly elected vice-president shall then assume the duties and title of president with all of the authority vested in him by the Constitution. In the event the vice-president shall not be able to assume said duties, then the succession shall be in the following order: past-president, secretary-treasurer. If none of the above mentioned members of the council shall be able to assume the office of the president, then a special election shall be held in which at least two qualified members, nominated by the council, shall be voted upon by the membership by means of a special mailed ballot. Any vacancies in the normally constituted council caused by such succession or for any other reason may be filled with a temporary appointment by the council.

4. Nominees for the office of president shall be active members in good standing, who shall have served (or may be serving concurrently at the time of nomination) as vice-president, secretary-treasurer, chairman of the Research Committee, or editor of one of the Society's official publications.

5. The vice-president shall be the officer of the council responsible for arrangements for the annual meeting, including selection of program chairmen, and shall keep in close contact with the Research Committee and others concerning technical papers and symposia to be presented.

ARTICLE IV. PUBLICATIONS

1. There shall be two editors, one for the *Journal of Paleontology* and one for the *Journal of Sedimentary Petrology*. The editors shall be in charge of editorial business of their respective Journals. Each shall submit an annual report of such business, shall have authority to solicit papers and material for such Journals, and may appoint associate or co-editors.

2. The *Journal of Paleontology* and the *Journal of Sedimentary Petrology* are designated as official publications of the Society. The council is not authorized to initiate and publish other periodicals.

3. A publication fund may be established consisting of an assignment of a portion of dues as designated by the council, and such donations as are specifically made for that purpose. The council is authorized to provide special publications from this fund as may be deemed desirable, and to fix terms for sale or other distribution of these publications.

ARTICLE V. FINANCIAL METHODS

1. No financial obligations shall be contracted without express sanction of the Society or council, but all ordinary incidental running expenses have sanction without special action.

2. Statements of accounts charged to the Society, other than miscellaneous running expenses, shall be approved by the president before the secretary-treasurer pays the amount out of funds of the Society not otherwise appropriated, and the receipted bill shall be held as the secretary-treasurer's voucher.

3. The secretary-treasurer shall have charge of the financial affairs of the Society and shall annually submit reports as secre-

retary-treasurer covering the fiscal year. He shall receive all funds of the Society, and, under the direction of the council, shall disburse all funds of the Society. He shall cause an audit to be prepared annually by a public accountant at the expense of the Society. He shall give a bond, and shall cause to be bonded all employees to whom authority may be delegated to handle Society funds. The amount of such bonds shall be set by the council and the expense shall be borne by the Society. The funds of the Society shall be disbursed by check as authorized by the council.

ARTICLE VI. BUSINESS REPRESENTATIVES

The president and the secretary-treasurer of the Society shall act as business representatives of the Society in the business committee of The American Association of Petroleum Geologists. These representatives shall conduct such business with the executive committee of the Association as is of mutual interest to the Society and the Association in the interims between the annual meetings of the Society and the Association. Approval of the action of these representatives on the part of the Society during any year is reserved to the council in session at the annual meeting at the close of that year. Questions remaining unsettled between the representatives of the Society and the executive committee of the Association shall be considered in a joint meeting of the council of the Society or its authorized representatives and the executive committee of the Association at the annual meeting of the Association at the close of the interim period during which such questions have arisen.

ARTICLE VII. SECTIONS

1. The establishment of local sections of the Society may be authorized by unanimous vote of the council approving a petition for such establishment signed by ten members of the Society. Such local sections may elect officers, conduct meetings, and engage in other scientific activities.

2. The council is authorized and directed to withdraw the charter of any established local section if there is evidence that it has become inactive.

ARTICLE VIII. DIRECTORS OF AMERICAN GEOLOGICAL INSTITUTE

1. The president and the past-president shall be directors of the American Geological Institute, the past-president being the senior director. They shall represent the Society on said Institute. The term of office as directors shall coincide with their term of president and past-president.

2. In the event of a vacancy by resignation, death, or other causes among the two directors who represent the Society on said Institute, the president of the Society shall nominate a director from the ranks of active members of the Society, and this director shall complete the unexpired term.

ARTICLE IX. REPRESENTATIVE ON NATIONAL RESEARCH COUNCIL

At the expiration of each three-year term, the president shall appoint a representative on the National Research Council to serve for a term of three years.

ARTICLE X. RESEARCH COMMITTEE

1. The objectives and duties of the Research Committee shall be to foster and encourage research; to advise the Society and council on research activities which may concern the Society, or which may be recommended or initiated under its sponsorship; to develop a symposium for the annual meeting if so requested; to select recipients for Best Paper Awards each year for each Journal; to nominate candidates for honorary members, correspondents, and patrons; and to deal with any other matters referred to it from time to time by the president or the council.

2. The activities of the Committee shall be directed by a chairman and a vice-chairman, to be appointed by the president, with the approval of the council, from the active members of the Committee. The term of the appointment of the chairman shall be one year. The vice-chairman will normally succeed the chairman the following year. In the event either of these offices is vacated for any reason, the council shall appoint a qualified replacement for the unexpired term.

3. Membership of the Committee shall be appointed by the president from members and associates of the Society. The

Committee shall consist of fourteen members, but this total may be changed at the discretion of the council. Two committee members, preferably one paleontologist and one mineralogist, shall be chosen from each of several geographic regions to be selected by the council. In addition, advisory members may be appointed from foreign areas. The terms of appointment of members and advisory members shall be for three years. Appointments shall be staggered, with the junior member from any region serving at least one year with the senior member from that region. If vacancies develop on the Committee the president shall make suitable appointments for the unexpired term.

ARTICLE XI. AMENDMENTS

The by-laws may be amended at any annual business meeting by two-thirds vote of the members present, or by mail ballot sent to the members, in which case two-thirds of the returned ballots received in sixty days after mailing must approve the amendment in order to make it effective. Any proposed changes to the by-laws must first have the approval of the council.

ERRATA

SUGGESTED USE OF BED THICKNESS MEASUREMENTS IN STRATI GRAPHIC DESCRIPTION

JOHN BOKMAN, 1957, Jour. Sedimentary Petrology, v. 27, p. 333–335

In "Suggested Use of Bed Thickness Measurements in Stratigraphic Description" by John Bokman, September 1957, on page 335 the statement that the standard deviation is equal to one-half the variance should read the *square root* of the variance. Consequently in Table 3,

$$s = \frac{1.36\theta}{2} = 0.68\theta = 1.60 \text{ in.}$$

should read $s = 1.36\theta = 1.17\theta = 2.25$ in.; and the standard deviation column in Table 1 should read:

θ	inches
0.99	1.99
1.01	2.01
0.69	1.61
1.30	2.46
1.17	2.25

Some implications of the procedure described also warrant additional comment.

The *theta* mean and standard deviation are not exactly equal to the corresponding arithmetic parameters of the distribution of actual measurements. This is so because grouping the bed thicknesses on the *theta* scale creates a new population, composed of logarithms of the original measurements. The arithmetic mean and standard deviation of this population are equal to the corresponding geometric, rather than arithmetic, parameters of the parent population.

The median and the difference between two selected percentiles are measures of central tendency and dispersion which were not previously mentioned. Their values for most bed thickness distributions differ somewhat from both the arithmetic and geometric means and standard deviations. They are particularly useful, however, due to the ease with which they can be obtained from a cumulative curve of bed thickness measurements.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 4, P. 476
DECEMBER, 1957

ANNOUNCEMENT

The annual Technical Meeting of the Permian Basin Section of the Society of Economic Paleontologists and Mineralogists will take place in Midland, Texas, on March 27, 28, and 29, 1958, according to Joseph P. D. Hall, Jr., Chairman of the Permian Basin Section committee. Registration and sessions will be at the Hotel Scharbauer.

W. A. Waldschmidt, 311 Leggett Building, Midland, Texas, is president of the Permian Basin Section; D. A. Zimmerman, 503 North Central Expressway, Richardson, Texas, will head the Technical Program Committee.

This announcement is made in the hope that serious conflicts with other meetings can be avoided on this date.

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March, 1958–March, 1959

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EDITOR'S NOTE ON THE STATE OF THE JOURNAL

The *Journal of Sedimentary Petrology* was expanded to 128 pages per issue beginning in June, 1957. This expansion has reduced the backlog of manuscripts on hand sufficiently to provide a much shorter delay in publication—well under a year's wait. The *Journal* can accommodate somewhat longer papers in the future.

In view of the increased size of the *Journal*, which is published in four numbers per year with an average of 128 pages each, and an increase of nearly 200 copies each year in its distribution list, investigators in the fields of sedimentary petrology are urged to consider the *Journal of Sedimentary Petrology* as a primary outlet for their manuscripts.

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Vol. 31 (1957), Nos. 1,2,3,4,5,6

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Vol. 1 (1931), No. 2
Vol. 2 (1932), Nos. 1,2,3
Vol. 3 (1933), Nos. 1,2,3
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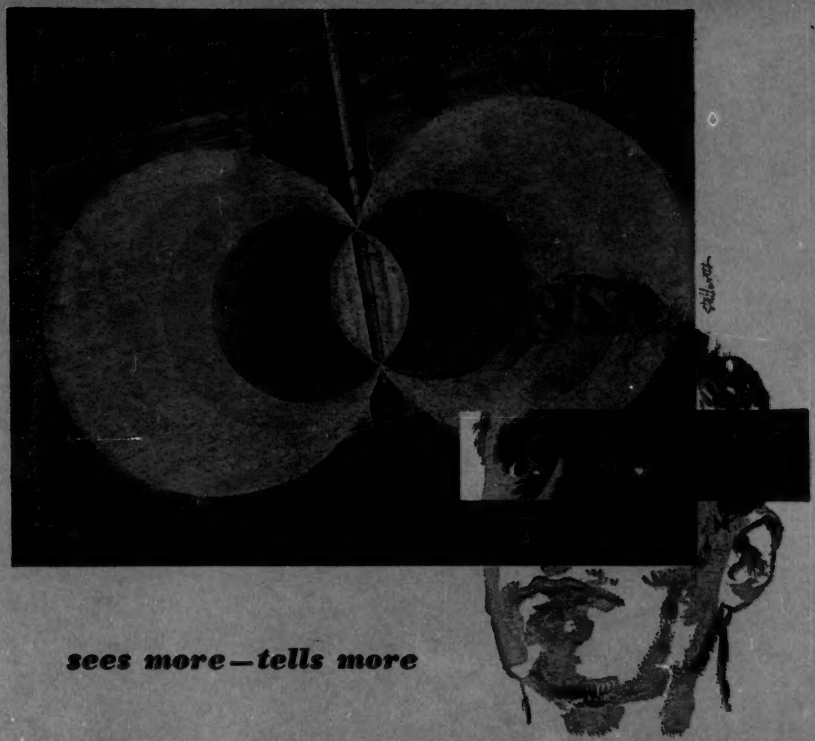

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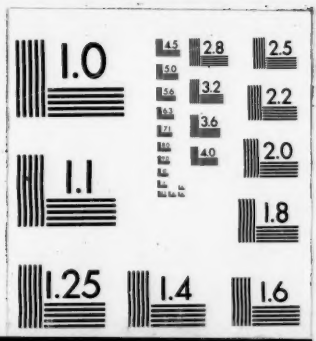
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